Journal of the Japanese Society for Sonic Arts, Vol.8 No.2 pp.7–16

Research Report

DEVELOPMENT OF ELECTRONIC INSTRUMENTS USING ANALOG PHOTO COUPLERS

Ichiro TSUJI

ABSTRACT

This paper proposes a method for controlling a multichannel amplifier and an analog filter, using control signals output from a USB device. By inputting a control signal into a multichannel amplifier, the localization of the audio signal that is input into the amplifier can be controlled using analog photo couplers. By inputting a control signal into an analog filter, the sensitivity, center frequency, and phase of the analog filter can be controlled using analog photo couplers. The control signal can be a conventional signal or a random signal, generated from a USB device using a computer program. Therefore, the localization of sound in a multichannel amplifier and the tone of an analog filter are freely controllable. By incorporating such techniques into a unique synthesizer, the system can be updated and the sound effects can be made richer.

1. INTRODUCTION

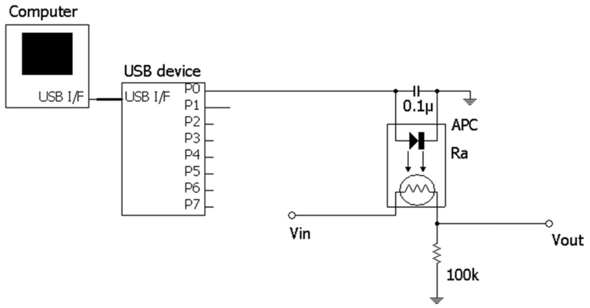
An analog photo coupler is used as an effector for the tremolo of the gain control, phaser of the phase control, etc. [1]. By changing the brightness of the light-emitting diode (LED) built into the analog photo coupler, the resistance of the photo register cadmium sulfide cell (CDS) can be modified to change gently. The project HPSCHD [2] of Cage and Hiller used 52 speakers; multichannel speakers are being increasingly used in the fields of experimental music or avant-garde music. These days, there are applications that can be used to control multichannel speakers [3]. A multichannel amplifier can apply voltage control to the input signal of one channel, using an analog photo coupler, and distribute it to the outputs of one or two channels. Hence, the localization of sound for two channel speakers can be controlled. The control signal input into an analog photo coupler is output from a USB device. As this control signal can be controlled by a program on a computer, the speeds of sound in the two channel speakers can be controlled effectively. The multichannel amplifier can control the localization of sound for five kinds of input signals. The analog filter can control the resistance, which in turn controls the sensitivity of a low-pass filter, the center frequency of a bandpass filter, and the phase of an all-pass filter, simultaneously, using an analog photo coupler. The control signal input into an analog photo coupler is output from a USB device as well as from a multichannel amplifier. Therefore, the tone of the analog filter can be controlled in several ways by a computer program.

2. DESIGN OF MULTICHANNEL AMPLIFIER

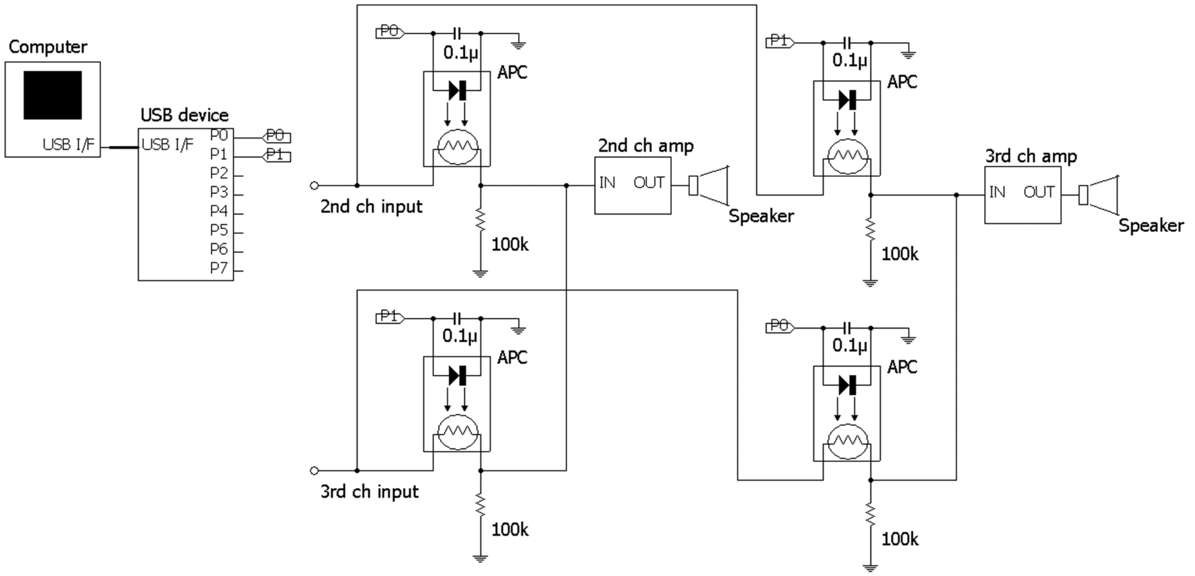
A multichannel amplifier is designed with six inputs and six outputs. The input of the first channel is output to the first channel, and the input of the sixth channel is output to the sixth channel. The input signals of the first and sixth channels change from OFF to ON in turns, using two pulse signals, which are control signals output by a USB device. The input signals of the second and third channels are distributed to the outputs of the second and third channels using two pulse signals, which are control signals output by a USB device. The input signals of the fourth and fifth channels are distributed to the outputs of the fourth and fifth channels using two pulse signals, which are control signals output by a USB device. An input signal is input into the voltage-control circuit, where the resistance of an analog photo coupler changes based on the control signal. An original voltage-control circuit, the voltage-control circuit used for the second and third channels of the multichannel amplifier, and the voltage-control circuit used for first and sixth channels of the multichannel amplifier are shown in Figure 1. When the resistance of the analog photo coupler is set as R_a, the transfer function of the voltage-control circuit can be expressed by formula (1), obtained from Figure 1(a). Formula (1) shows that the voltage V_{out} of an output signal will decrease if the value of R_a increases and that V_{out} will increase if the value of R_a decreases. V_{in} represents the input voltage. The waveform of the output signal for this voltage-control circuit is shown in Figure 2. In Figure 2, the pulse signal in blue represents the control signal, and the pulse signal in red represents the output signal. Because the output signal is amplified quickly and reduced gently, a smooth sound speed can be realized, as the value of resistance increases gently.

$$T_0 = \frac{V_{out}}{V_{in}} = \frac{10^5}{R_a + 10^5} \tag{1}$$

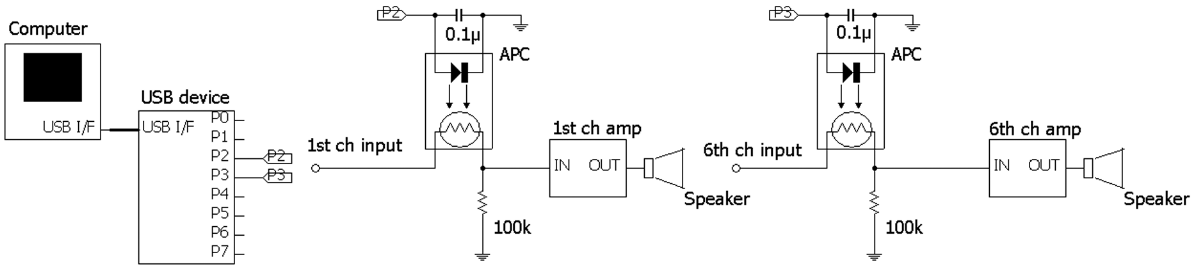
When a control signal has a constant value of 5 V (referred to as high, hereafter), the frequency characteristics of the voltage-control circuit in Figure 1(a) are shown in Figure 3 (in red). It can be observed that the signal decreases gently after 300 Hz, and it turns out that the signal has decreased by nearly 20 dB at 20 kHz. When the control signal is at a constant voltage of 0 V (referred to as low, hereafter), the frequency characteristics of the voltage-control circuit in Figure 1(a) are shown in Figure 3 (in blue). It turns out that the output signal is mostly silent. The frequency characteristics of this voltage-control circuit were



(a) Original voltage-control circuit



(b) Voltage-control circuit used for the second channel and the third channel



(c) Voltage-control circuit used for the first channel and the sixth channel

APC : Analog photo coupler

Figure 1. Method of voltage control

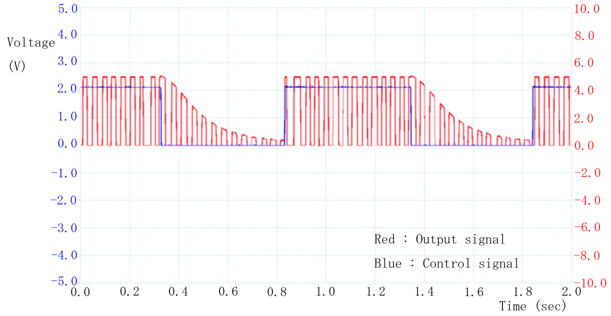


Figure 2. Output signal of a voltage-control circuit

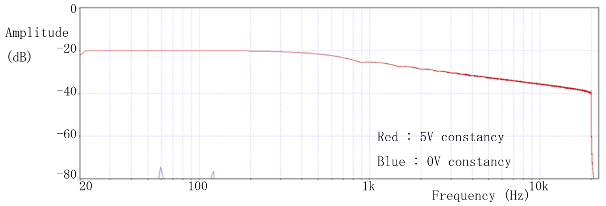
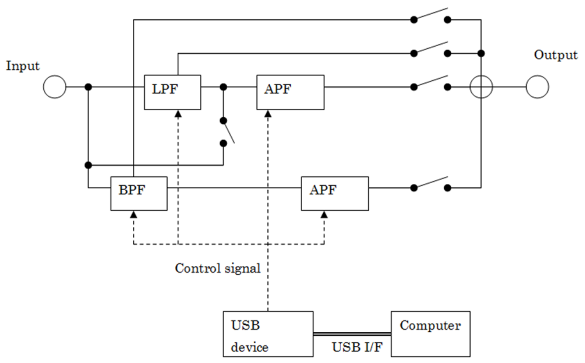
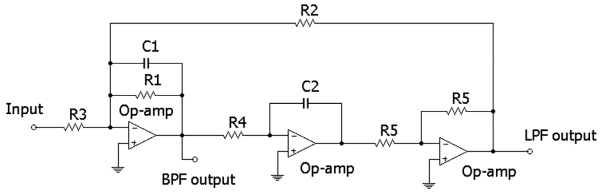


Figure 3. Frequency characteristics of a voltage-control circuit



LPF : Low-pass filter, BPF : Bandpass filter, APF : All-pass filter

Figure 4. Basic structure of an analog filter



LPF : Low-pass filter, BPF : Bandpass filter

Figure 5. Biquad circuit

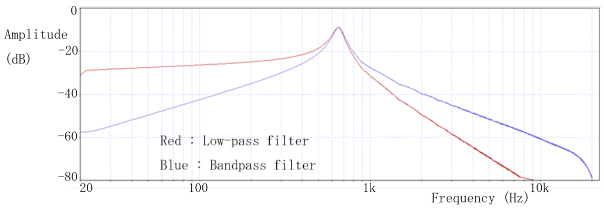


Figure 6. Frequency characteristics of a biquad circuit

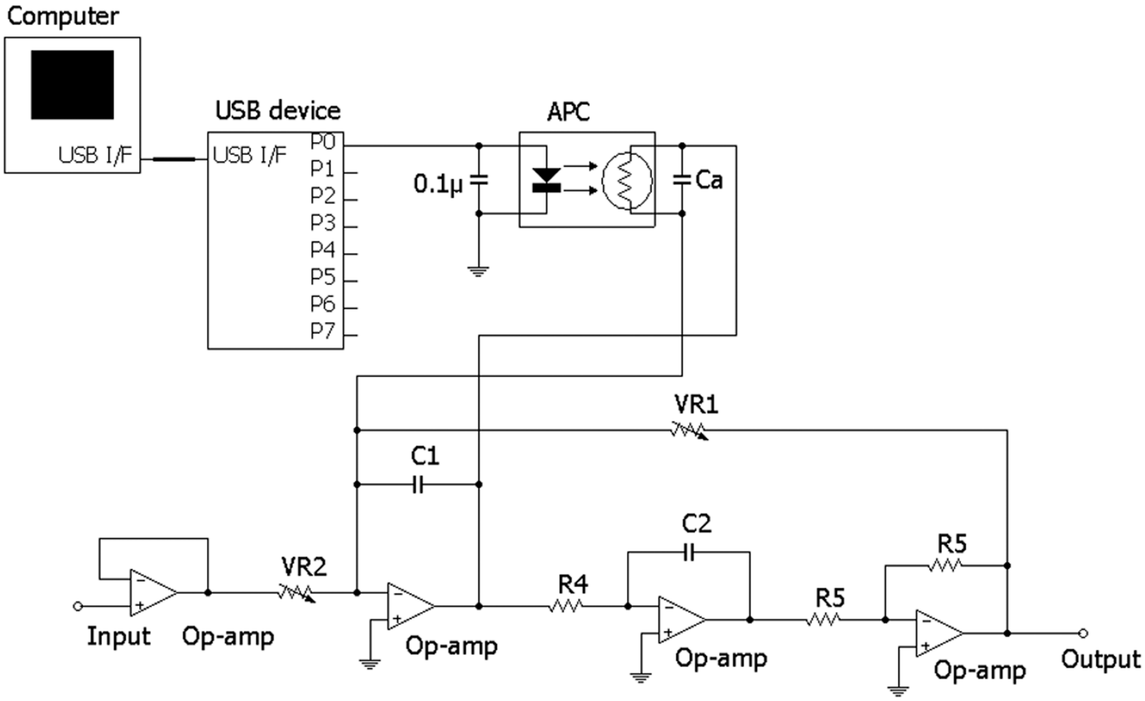
measured using WaveGene and WaveSpectra of efu [4]. For the voltage control of the second and the third channels of the multichannel amplifier, shown in Figure 1(b), the control signal is controlled by a program on a computer. Two control signals are output from the digital I/O ports P0 and P1 of a USB device. When the output signal of P0 is high, the output signal of P1 will be low, and when the output signal of P0 is low, the output signal of P1 is set to high by a computer program. When the control signal is high, the input signal to the amplifier is set to ON, and when the control signal is low, the input signal to the amplifier becomes OFF. For example, when P0 is high, the input signal of the second channel is input to the amplifier of the second channel. At this time, P1 is set to low so that the input signal of the second channel is not input into the amplifier of the third channel. When P1 is low, the input signal of the third channel is not input to the amplifier of the second channel, and because P0 is high, the input signal of the third channel is input into the amplifier of the third channel. The control of the input signals of the fourth and fifth channels is also achieved in a similar manner using control signals. USB-FSIO30 [5] of Km2net was used as the USB device. This USB device was prepared using the Dynamic-Link Library (DLL), which can code in Visual Basic 2010 Express from the Microsoft Corporation[1] . Thus, a control signal can be easily generated by a computer program, and the input signal of a multichannel amplifier can be controlled. The half-period $hp1$ of the pulse signal used as the control signal is expressed by formula (2), and is set to vary between 1 ms and 10000 ms within a range of maximum hp_max1 and minimum hp_min1. rnd represents a random number between 0 and 1, of the float type. $CInt$ represents an integer-type transfer function. However, the half period in a computer program is not in strict agreement with the half period of the signal output from a USB device.

$$\begin{aligned} hp1 &= CInt(hp\_max1 \times rnd) \\ &(\quad hp1 \geq hp\_min1) \\ hp1 &= hp\_min1 \\ &(\quad hp1 < hp\_min1) \end{aligned} \tag{2}$$

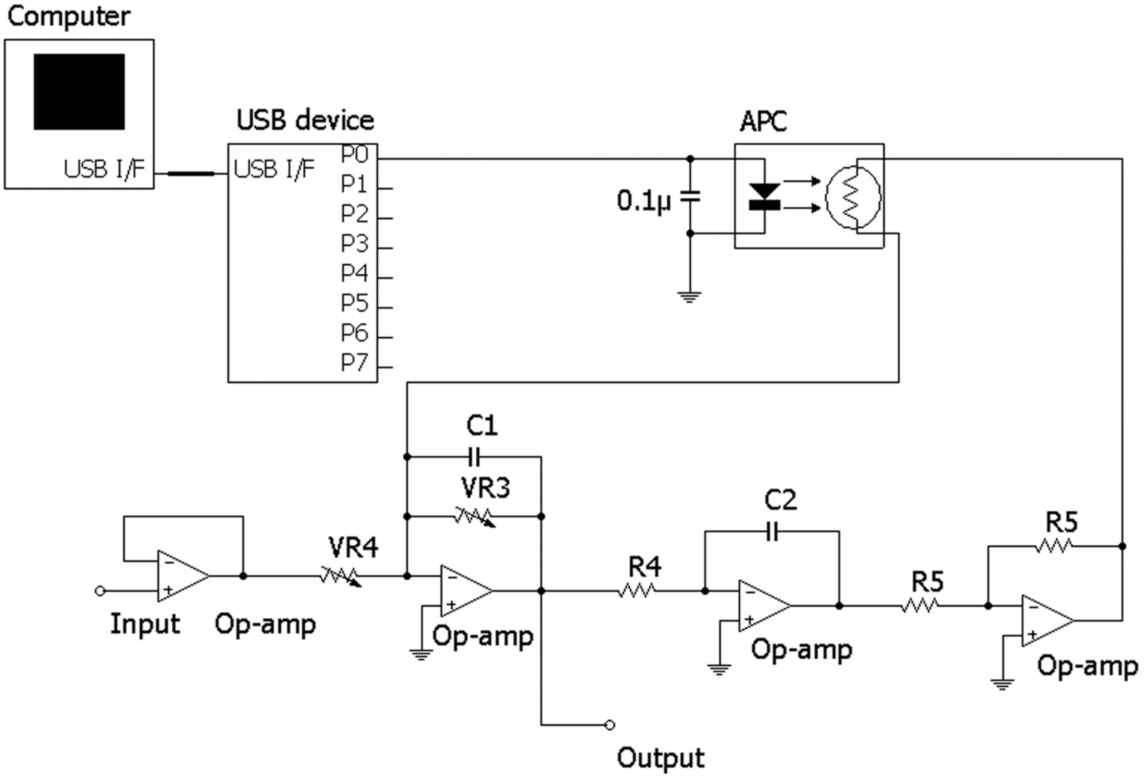
In cases where the control signal was a conventional signal, it was set as a rectangular wave with a duty factor of nearly 50%; in cases where the control signal was a

---

[1] https://www.microsoft.com/ja-jp/



(a) Low-pass filter that controls the sensitivity



(b) Bandpass filter that controls the center frequency

APC : Analog photo coupler

Figure 7. Biquad circuit that controls sensitivity and center frequency

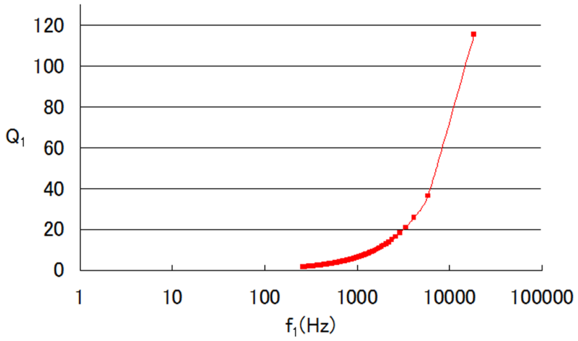


Figure 8. Relationship between the frequency cutoff f_1 and the sensitivity Q_1

random signal, a pulse-width modulated (PWM) signal, whose duty factor changed in each period was used. In cases where the sound image had not changed, P0 was set to high and P1 was set to low. At the start of a performance, or at the end of a performance, both P0 and P1 were set to low. Whenever the type of input signal to a multichannel amplifier or a musical instrument's performance method changed, a probability function was used and the type of control signal was determined. By generating such a control signal, the speeds of the sound could be varied between two channel speakers. As for the voltage control of the first and sixth channels of a multichannel amplifier (Figure 1(c)), a control signal was controlled by a program on a computer. Two control signals were output from the digital I/O ports P2 and P3 of a USB device. When the output signal of P2 was high, the output signal of P3 served as low, and when the output signal of P2 was low, the output signal of P3 was set to high by the program on a computer. The analog filter is described in the next section, and the signal used in the analog filter can be used as the control signal. Thereby, sound-image control can be achieved according to the changes in timbre.

3. DESIGN OF ANALOG FILTER

The basic structure of the designed analog filter is shown in Figure 4. The circuit structure in Figure 4 consists of a cascaded connection of a low-pass filter and a bandpass filter with several all-pass filters. The sections below describe the control of the sensitivity of a low-pass filter, the center frequency of a bandpass filter, and the phase of an all-pass filter.

3.1. Control of sensitivity and center frequency

The circuit diagram of a biquad circuit [6] that is used for the design of a low-pass filter and a bandpass filter is shown in Figure 5. An example of the frequency characteristics of the biquad circuit is shown in Figure 6. The characteristics in red represent the frequency characteristics of a low-pass filter, and the ones in blue represent the frequency characteristics of a bandpass filter. The frequency characteristics of the biquad circuit were measured using WaveGene and WaveSpectra of efu [4]. The transfer function of a low-pass filter is expressed by formula (3), using a transfer function of the second order $T_{LP} = \dfrac{\omega_1^2}{s^2 + \dfrac{\omega_1}{Q_1}s + \omega_1^2}$.

$$
\begin{aligned}
T_1 &= \frac{-\dfrac{1}{C_1C_2R_3R_4}}{s^2 + \dfrac{s}{C_1R_1} + \dfrac{1}{C_1C_2R_2R_4}} \\
\omega_1 &= \sqrt{\frac{1}{C_1C_2R_2R_4}} \\
Q_1 &= R_1C_1\omega_1 \\
G_1 &= \frac{R_2}{R_3}
\end{aligned}
\tag{3}
$$

where T_1 and T_{LP} represent the transfer function of a low-pass filter, ω_1 represents the angular frequency, Q_1 represents the sensitivity, and G_1 represents the gain. R_1, R_2, R_3, and R_4 represent the resistances, and C_1 and C_2 represent the capacitances in Figure 5. The transfer function of a bandpass filter is expressed by formula (4), using a transfer function of the second order $T_{BP} = \dfrac{\dfrac{\omega_2}{Q_2}s}{s^2 + \dfrac{\omega_2}{Q_2}s + \omega_2^2}$.

$$
\begin{aligned}
T_2 &= \frac{-\dfrac{1}{C_1R_3}}{s^2 + \dfrac{s}{C_1R_1} + \dfrac{1}{C_1C_2R_2R_4}} \\
\omega_2 &= \sqrt{\frac{1}{C_1C_2R_2R_4}} \\
Q_2 &= R_1C_1\omega_2 \\
G_2 &= \frac{R_1}{R_3} \\
BW_2 &= \frac{\omega_2}{Q_2}
\end{aligned}
\tag{4}
$$

where T_2 and T_{BP} represent the transfer function of a band-pass filter, ω_2 represents the angular frequency, Q_2 represents the sensitivity, and G_2 represents the gain. The low-pass filter in Figure 4 is replaced with the analog photo coupler from the resistance R_1 in Figure 5, which controls the sensitivity of the biquad circuit. The bandpass filter in Figure 4 is replaced with the analog photo coupler from the resistance R_2 in Figure 5, which controls the center frequency of the biquad circuit. The equivalent circuit diagrams of each filter are shown in Figure 7. In Figure 7, VR_1 is equivalent to the resistance R_2 of Figure 5, and it represents the variable resistance that controls the frequency cutoff. VR_2 and VR_4 are equivalent to the resistance R_3 of Figure 5, and they represent the variable resistance that controls the gain. VR_3 is equivalent to the resistance R_1 of Figure 5, and it represents the variable resistance that controls the sensitivity. However, VR_1 affects the values of sensitivity and gain as per formula (3). VR_3 affects the value of gain according to formula (4). For example, a biquad circuit can be designed to set the

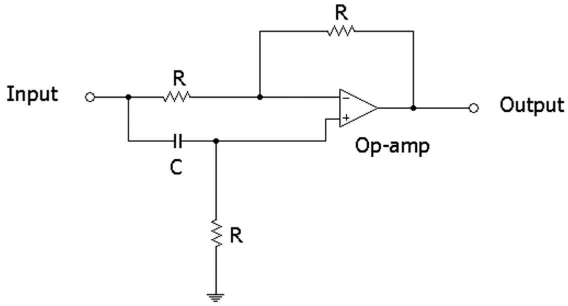


Figure 9. All-pass filter

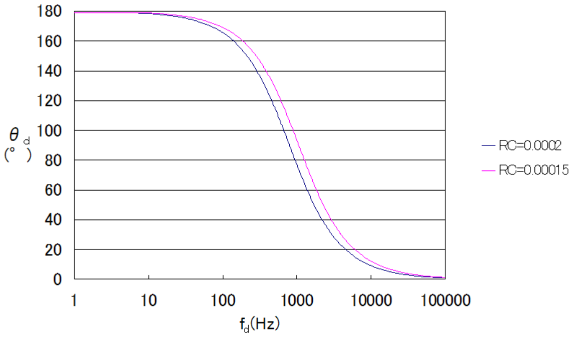


Figure 10. Phase characteristics of an all-pass filter

sensitivity Q_1 to nearly 1.6 for a frequency cutoff f_1 of nearly 260 Hz from formula (3). The relationship between the frequency cutoff f_1 and the sensitivity Q_1 is expressed as shown in Figure 8. From Figure 8, it can be observed that, in order to lower the value of Q_1, it is necessary to lower the value of the resistance R_1 from formula (3). In Figure 7, the control signal output from the digital I/O port of the USB device is input into an analog photo coupler. Because the value of resistance in the analog photo coupler increases gently, it can be assumed that the value of sensitivity also increases gently and that the value of center frequency decreases gently. USB-FSIO30 [5] of Km2net was used as the USB device as well as the multi-channel amplifier. The half-period $hp2$ of the pulse signal used as a control signal is expressed by formula (5), and is set to vary between 1 ms and 2000 ms within a range of maximum hp_max2 and minimum hp_min2. rnd represents a random number between 0 and 1, of the float type. $CInt$ represents an integer-type transfer function. However, the half period in a computer program is not in strict agreement with the half period of the signal output from a USB device.

$$\begin{aligned} hp2 &= CInt(hp\_max2 \times rnd) \\ &\quad (\quad hp2 \geq hp\_min2) \\ hp2 &= hp\_min2 \\ &\quad (\quad hp2 < hp\_min2) \end{aligned} \tag{5}$$

In cases where the control signal was a conventional signal, it was set as a rectangular wave with a duty factor of nearly 50%; in cases where the control signal was a random signal, a PWM signal, whose duty factor changed in each period was used. The control signal was set to high in cases where the sensitivity and center frequency were not changed. The control signal was set to low in cases where there was no input signal. Whenever the type of input signal to an analog filter or a musical instrument's performance method changed, a probability function was used, and the type of the control signal was determined. Various timbres could be obtained by generating such control signals. The capacitor C_a, connected in parallel with the analog photo coupler of Figure 7(a), suppressed the oscillations in a biquad circuit.

3.2. Control of phase

An all-pass filter for a phase shift of θ_d corresponding to an angular frequency of ω_d is shown in Figure 9 [6]. The transfer function T_3 of the all-pass filter is expressed by formula (6). R represents a resistor and C represents a capacitor in Figure 9.

$$T_3 = \frac{s - \dfrac{1}{RC}}{s + \dfrac{1}{RC}} \tag{6}$$

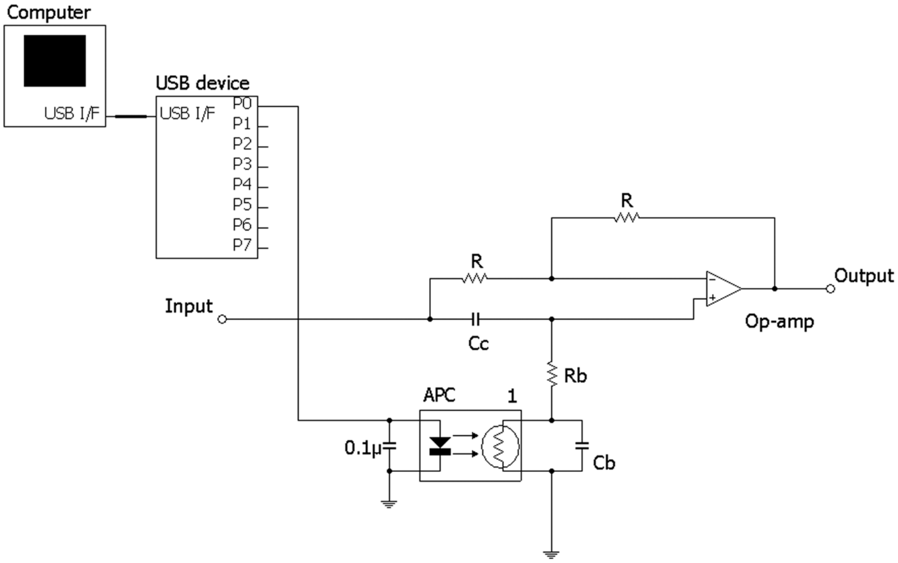
The range of the phase shift θ_d is expressed by formula (7).

$$0^\circ < \theta_d < 180^\circ \tag{7}$$

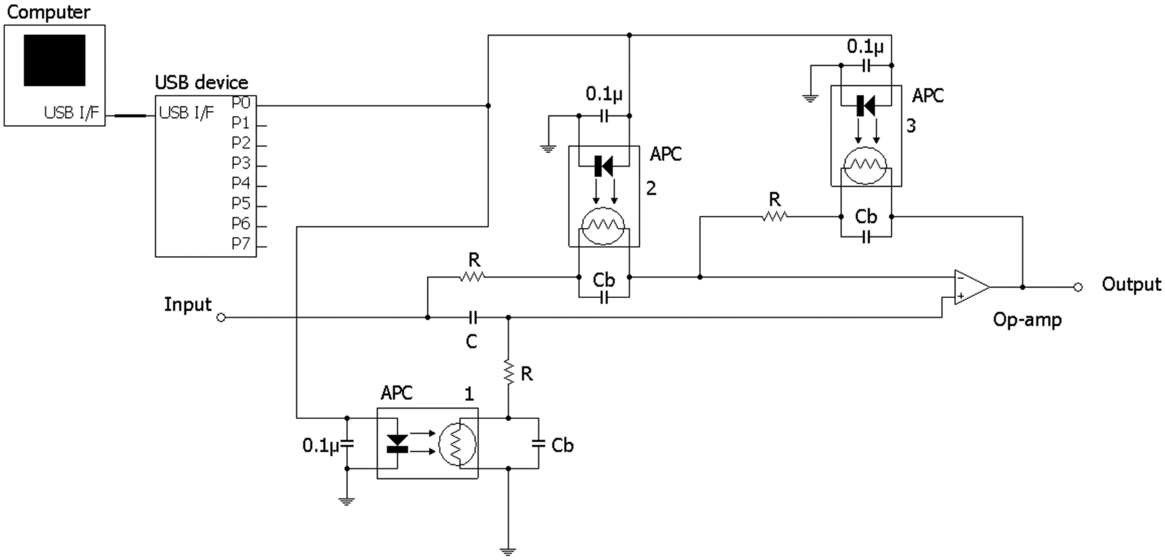
The resistance R and the capacitance C in Figure 9 are obtained as per formula (8).

$$RC = -\frac{\tan \dfrac{1}{2}(180^\circ + \theta_d)}{\omega_d} \tag{8}$$

An example of the phase characteristics for the all-pass filter obtained from formula (8) is shown in Figure 10. From Figure 10, it can be observed that, if the frequency f_d decreases, the phase θ_d approaches 180°, and if the frequency f_d increases, the phase θ_d approaches 0°. The all-pass filter of Figure 4 is used to control the phase by using a cascaded connection of an analog photo coupler with the resistance R from Figure 9. This circuit diagram is shown in Figure 11 (b). The capacitor C_b, connected in parallel with the analog photo coupler of Figure 11 removes the noise generated by the analog photo coupler. The all-pass filter, which is in a cascaded connection with the low-pass filter of Figure 4, is designed such that θ_d shifts to 160° at a frequency of nearly 187 Hz. The all-pass filter, which is in a cascaded connection with the bandpass filter of Figure 4, is designed such that θ_d shifts to 160° at a frequency of nearly 140 Hz. However, the value of resistance for an analog photo coupler is not taken into consideration. In Figure 11(b), the control signal output from the digital I/O port of the USB device is input into the analog photo coupler of the all-pass filter. USB-FSIO30 [5] of Km2net was used as the USB device as well as the multichannel amplifier. From Figure 4, it can be observed that the control



(a) Conventional all-pass filter using analog photo coupler 1



(b) All-pass filter using analog photo coupler 2 and analog photo coupler 3

APC : Analog photo coupler

Figure 11. All-pass filter that controls the phase

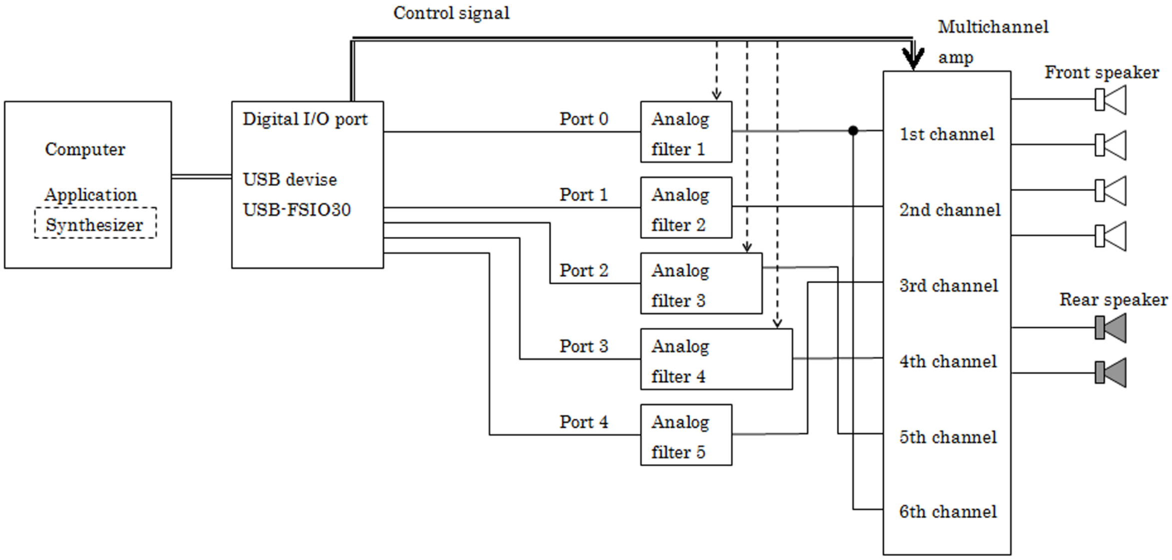
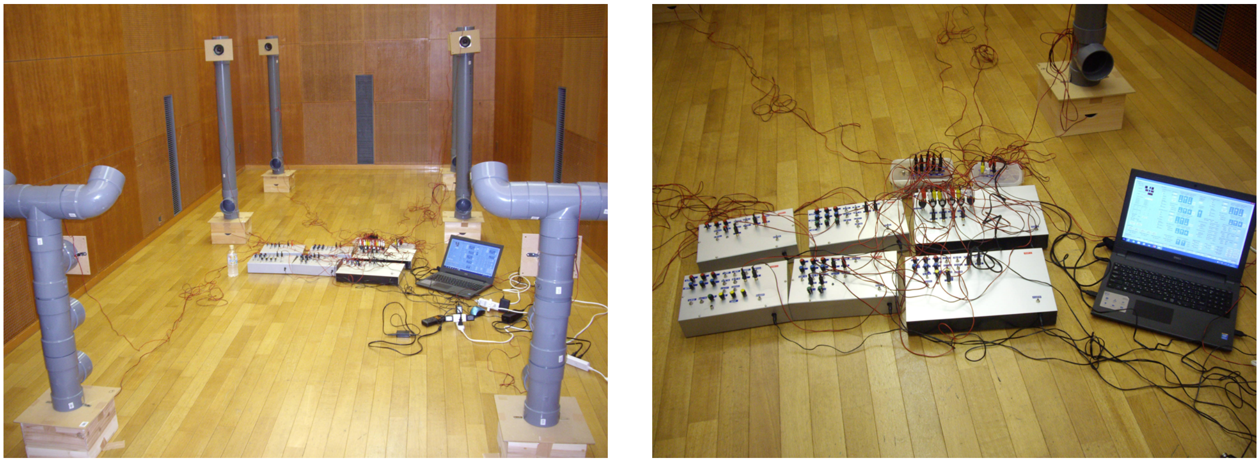


Figure 12. Basic structure of a synthesizer system



(a)Complete system

(b)Sound-source part

Figure 13. Actual synthesizer system

signal of the all-pass filter is the same signal that is used as the control signal in the low-pass and bandpass filters. From Figure 11(a), it can be seen that the conventional all-pass filter controls the phase using the analog photo coupler 1 only. The frequency f_e required for a phase shift of 90° is given by formula (9) [1].

$$f_e = \frac{1}{2\pi R_b C_c} \tag{9}$$

where R_b represents the resistor, and C_c represents the capacitor in Figure11(a). The timbre of the all-pass filter in Figure 11(b) that uses the analog photo coupler 2 and the analog photo coupler 3 is different from that of the conventional all-pass filter in Figure 11(a).

4. APPLICATION TO A SYNTHESIZER SYSTEM

The basic structure of a synthesizer system that uses the proposed multichannel amplifier and analog filter is shown in Figure 12. The photograph of an actual synthesizer system is shown in Figure 13. The photograph of the complete system is shown in Figure 13(a). The photograph of the sound-source part consisting of a synthesizer, analog filters, and a multichannel amplifier is shown in Figure 13(b). The synthesizer consists of a computer and a USB device. The PWM signal output from the USB device can be controlled by a program on a computer, and automatic composition can be carried out [7]. In Figure 12, the output terminals of a synthesizer are referred to as Port 0, Port 1, Port 2, Port 3, and Port 4, and a PWM signal is output from each output terminal. The output signal of Port 0 is input into the first and sixth channels of a multichannel amplifier through analog filter 1 fabricated for this

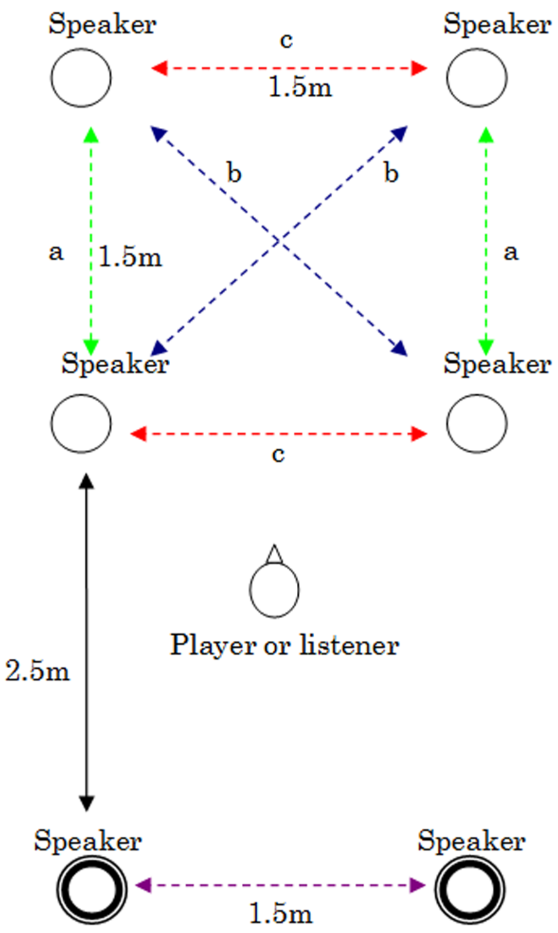


Figure 14. Top view of the speaker units

research. The output signal of Port 1 is input to the second channel of the multichannel amplifier through analog filter 2. The output signal of Port 2 is input to the fifth channel of the multichannel amplifier through analog filter 3. The output signal of Port 3 is input to the fourth channel of the multichannel amplifier through analog filter 4. The output signal of Port 4 is input to the third channel of the multichannel amplifier through analog filter 5. Ten control signals are output from the digital I/O port of a USB device. One control signal is input into analog filter 1, and it controls the sensitivity of the low-pass filter, the center frequency of the bandpass filter, and the phase of the all-pass filter. Two control signals are input into analog filter 3, and they control the frequency cutoff of the low-pass filter, and the center frequency of the bandpass filter. Six control signals are input into the multichannel amplifier, and they control the input signals to all channels, from the first channel to the sixth channel. One control signal is input into analog filter 4, and it controls the phase of the all-pass filter. In the cases of analog filter 2 and analog filter 5, the low-pass filters and the bandpass filters were designed using the biquad circuit, and the high-pass filters were designed using the Sallen-Key circuit [6]. As for analog filter 3, the low-pass filter and the bandpass filter were designed using the biquad circuit. Analog filter 4 was designed such that a biquad circuit and an all-pass filter were in a cascaded connection. A cascaded connection of two all-pass filters was implemented in which each all-pass filter provided a phase shift of 90° at a frequency of nearly 7962 Hz [1]. However, the value of resistance for an analog photo coupler was not taken into consideration. The all-pass filter was designed using the conventional all-pass filter in Figure 11(a). The output signals from a multichannel amplifier were input into the front speaker units and the rear speaker units, and were played back [8]. The top view of the speaker units is shown in Figure 14. In Figure 14, the front speaker units are arranged in the form of a square with 1.5-m sides. The two rear speaker units, which play back the outputs of the first and sixth channels of a multichannel amplifier, are arranged with a 1.5-m-wide spacing behind the player or the listener. The spacing between the front speaker units and the rear speaker units is 2.5 m. The outputs from the second channel to the fifth channel of a multichannel amplifier switch the connections of the front speaker units. As the speed of sound can demonstrate three kinds of orientations between the front speaker units : (a) along the vertical direction, (b) along the diagonal line, and (c) along the horizontal direction, the speeds of sounds were designed for changing the acoustic features according to music. The rear speaker units could support speeds of sounds in the horizontal direction only.

5. CONCLUSION

This paper presented an effective method for achieving logical automatic composition by attempting to control a multichannel amplifier and analog filters, using the control signals output by a USB device. The attempt could control the audio synthesis and the localization of sound, through a program on a computer. Because the digital filter on the computer, which was controlling based on the probability only was not used this time, the repeatability of the music increased as it was being composed by a computer. In the future, I would like to carry out experiments for improving the tone quality of an analog filter and reexamine the speaker units and the special sound effects by an analog filter.

6. REFERENCES

[1] Otsuka, Akira. *Saundo·Kuriāta notameno Efekuta Seisaku Kouza (The Effector Manufacture Lecture for a Sound Creator)*. Yousensha, 2015.

[2] Husarik, Stephen. *"John Cage and LeJaren Hiller: HPSCHD, 1969"*. American Music. 1983, Vol.1, No.2, pp.1-21.

[3] Miyama, Chikashi; Dipper, Götz ; Brümmer, Ludger . *"Zirkonium MKIII-a Toolkit for Spatial Composition"*. Journal of the Japanese Society for Sonic Arts. 2015, Vol.7, No.3, pp.54-59.

[4] efu. *efu's page*. 2014-08-01.

http://efu.jp.net/index.html, (accessed 2016-09-03).

[5] Komatsu, Hirofumi. *Kantan ! USB de Ugokasu Denshi Kousaku (Easy! Electronic Engineering with USB)*. Ohmsha, 2011.

[6] Van Valkenburg, M.E. *Analogu Firuta no Sekkei (A Design of an Analog Filter)*. Yanagisawa, Takeshi; Kanai, Hajime, trs. Akibashuppan, 1989.

[7] Tsuji, Ichiro. *“A Development of the Synthesizer Using a USB Device”*. Journal of the Japanese Society for Sonic Arts. 2015, Vol.7, No.1, pp.6-11.

[8] Tsuji, Ichiro. *“Investigation of the Sound-Field Playback System for PWM Signals”*. Japanese Society for Sonic Arts. 2015, Vol.7, No.3, pp.19-27.

7. AUTHOR’S PROFILE

Ichiro TSUJI

Born in 1966. Graduated from the Department of Electrical Engineering of the Kokushikan University in 1991. In 1986, in Tokyo, he started working on noise/industrial music for his band named “Dissecting Table.” He returned to his hometown 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 the labels of Europe and the United States. The first and middle stages were mainly dedicated to creating the work, by controlling the synthesizer and the sampler using a sequencer. From 2011, the works have been produced by controlling PWM signals output from a USB device on a computer.