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Relationship between Drive Signal and Stability in MIDS Modulator

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ABSTRACT

We propose a matrix driving method using a multi-input delta-sigma (MIDS) modulator to drive a large number of speakers. The MIDS modulator shares a single quantizer among multiple ΔΣ modulators and is able to drive the speaker array using the multiplication output individually and simultaneously even though the wiring is common. In other words, N × Nch speaker arrays can be driven individually with 2 × N wirings, instead of using time division as in imaging devices.

In this paper, we discuss the relationship between the drive method and stability for these MIDS modulators. In general, it is known that input signal amplitude of the ΔΣ modulator is limited by the peak value of the transfer function for quantization noise. Meanwhile, in the MIDS modulator can be used as a common quantizer for multiple signals, and the quantization noise from each input signal can be related to the other input signals. Therefore, simulations are performed to confirm the limit values of the input signals at the time of driving by the MIDS modulator. In the simulation, we compare the method combined with the random signal and the method of quantizing the modulator alternately by the X- and Y- axes. Consequently, in the proposed method, the stable input range is determined by the sum of the energies of the input signals regardless of the drive method, while the stable pole location differs depending on the drive method.

Keywords: Loudspeaker array, Multi-input delta-sigma modulator, MIDS, Super-multichannel processing, 1bit signal processing

1. INTRODUCTION

Sound waves are physical phenomena by which three-dimensional vibrations propagate; however, to reproduce an arbitrary wavefront strictly based on the Huygens principle, it is necessary to set control points, such as speakers, every half-wavelength distance for the target frequency band. We have constructed a recording/reproducing system, such as a 1024 channel microphone array, that satisfies the sampling theorem in space by using high-speed 1-bit signal processing [1]. However, it is difficult to construct a large-scale system by individually wiring each element; therefore, a method capable of controlling multiple points with a simpler structure is desired.

In a normal speaker, because the voltage difference between terminals is proportional to the acoustic output, it is inevitable that a strong correlation exists between the outputs when multiple speaker elements are driven using a common wiring. However, these problems may be solved if the speaker output is proportional to the product of the voltages between the terminals. Therefore, we propose a multichannel drive method that introduces multi-input delta–sigma (MIDS) modulation to encode signals input to a speaker array drive system using the multiplication output transducer array [2-4]. In the proposed method, a free structure wherein the inputs are combined with random signals or alternately quantized in the X- and Y-axes is possible. Therefore, we compare the stabilities of the input signals and pole locations between the two drive methods in this study.

2. MULTI-INPUT DELTA-SIGMA MODULATOR

2.1 Driving by common wiring

To construct a speaker array of extremely high density and a large number of channels, the individual-wiring method shown in Fig. 1 poses an implementation limit. Alternatively, in a speaker

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array in which the wiring is common, the outputs are proportional to the difference signals and always exhibit a correlation. In an imaging device, a multichannel drive with common wiring is realized for scanning; however, a hardware limitation exists in the drive of the sound signal, thus requiring high sampling and dynamic ranges compared with those for images. Further, it is difficult to increase the scale of the structure in which an IC is installed for each element. Therefore, in this research, we use a speaker that radiates an output proportional to the product of two input control signals, and consider an array to connect those speakers with common wiring. The scheme for this is shown in Fig. 2. By using speakers that output the multiplication result, it is possible to drive individually although it is common wiring. For example, considering an array in which 1-bit signals (1, -1) are output, as shown in Fig. 3, it can be easily noted that each speaker output is determined only by the combination of the respective input lines. With such a structure, individual control of the N × N channel can be performed with 2 × N control signals as shown in Fig.2. As array control using a multiplication output speaker and common wiring, a structure using an electrostrictive element is proposed[5]. and a method using the Semi Discrete Decomposition for generating drive signals is proposed[6-7]. However, the multiplication output structure is weak to noise between steps on hardware when the drive signal is composed of multibit, and the effective sampling frequency is limited in time division driving.

Therefore, the purpose of this research is to realize a speaker array that can be driven passively and individually while having common wiring, not being driven by time division, and additionally can be driven with 1-bit signal. Hence, we propose the MIDS modulator as a method of generating signals.

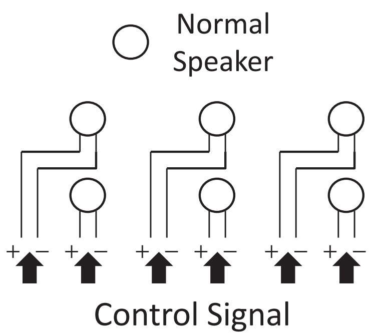


Fig 1 – Individually wired array

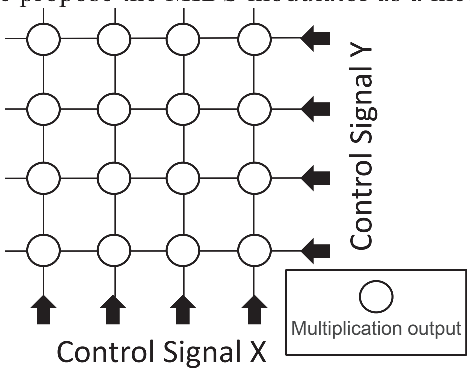


Fig 2 – Array using common wiring with multiplication output

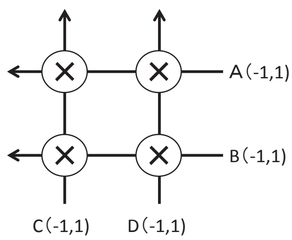


Fig 3 – Combination of 1-bit signal

2.2 Delta Sigma modulator

Δ Σ modulation is widely known as a quantization method for continuous signals such as sound signals[8]. It is a method of controlling the frequency characteristic of quantization noise by feeding back the quantizer output and obtaining a dynamic range in a desired band even with low bit quantization. The output of the first-order ΔΣ modulator, which is the basic structure, is shown in Eq. (1); the block diagram is shown in Fig. 4, and the spectrum of the simulation result of the output signal when a sine wave is input is shown in Fig. 5. As shown, the dynamic range of the audible range is obtained while the number of quantization bits is 1.

$$V = U + (1 - Z^{-1})Nq \tag{1}$$

V : Quantized signal U : Input signal Nq : Quantization noise for Qin

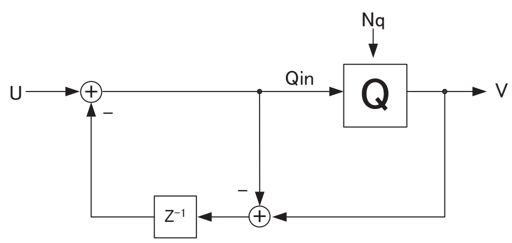


Figure 4 – First-order ΔΣ modulator

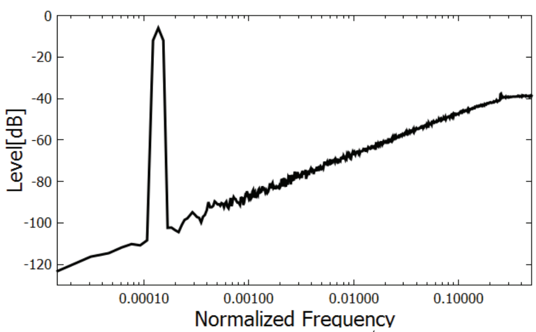


Figure 5 – Spectrum of output by 1^{st}-order ΔΣ modulator

2.3 MIDS modulator

As a method of generating a signal for driving a multiplication-output-type speaker array described in Section 2.1, we proposed the MIDS. A block diagram of the proposed method with four inputs/outputs and one quantization output is shown in Fig. 6. Unlike the normal ΔΣ modulator, the quantizer is common to multiple ΔΣ modulators and the product of the quantizer output Y and the individual signals X_1 to X_4 is the output of each channel. The basic idea of the proposed method is that although the control signal is common, the errors generated at each point are individually fed back and noise shaping is applied. In this method, X_1 to X_4 must be instantaneously uncorrelated with each other to output individual signals. The common quantizer Q ' produces an output that minimizes the sum of the error energy, which becomes Eq. (2) when driving with a 1-bit signal.

$$Y = \mathrm{sgn}\left[\sum_{k=1}^{N} X_k \times Qin_k\right] \tag{2}$$

As an example, consider a system in which four points are controlled by four M-sequence signals (random signals) and one control line, as shown in Fig. 7. The spectrum of each output (the product of the common quantizer output and each random signal) by the modulator is shown in Fig. 8. Different sine waves were used for the input signal. As shown, the input signals were output while maintaining their independence, and noise shaping was applied.

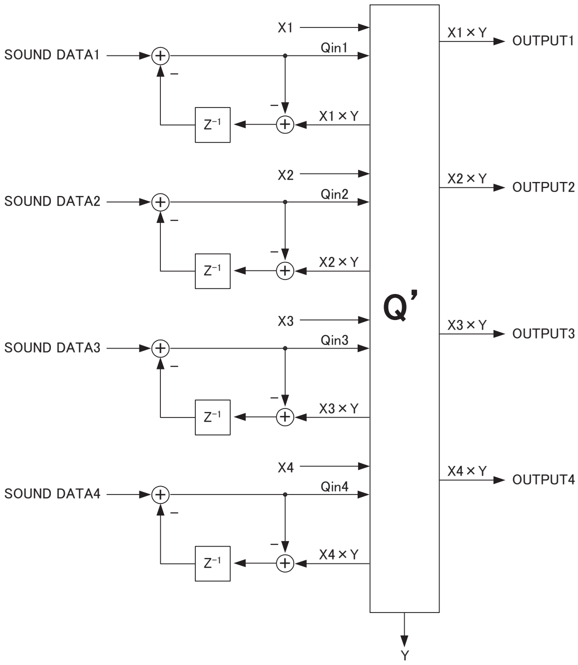


Figure 6 – Block diagram of the proposed method (first-order modulator)

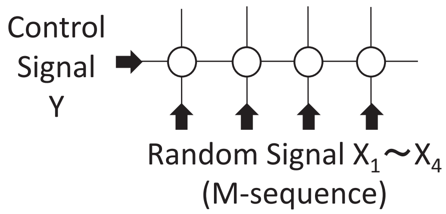


Figure 7 – Combination with random signal

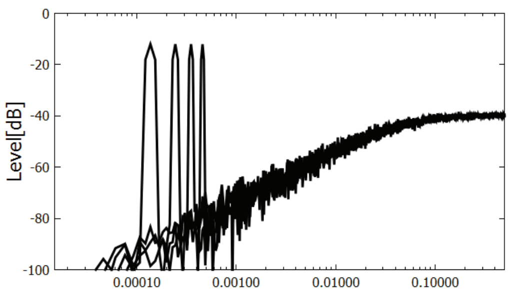


Figure 8 – Simulation results for four channels

Furthermore, when viewed from one channel, as shown in Fig. 9, the quantizer input of the other channel can be considered to be added as a whitened dither signal by being multiplied by the individual signal X. Assuming that these assumptions hold, $\sqrt{N}$ times whiteness dither can be added to Qin in the channel units. That is, if the level of Nq is considered to be constant, it can be regarded as equivalent to having a gain $k = \sqrt{N}$ in front of the quantizer, as shown in Fig. 10. Furthermore, the transfer function of this equivalent block diagram is Eq. (3).

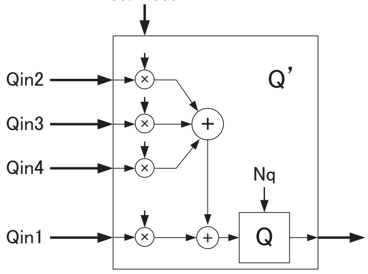


Figure 9 – Quantizer seen from one channel

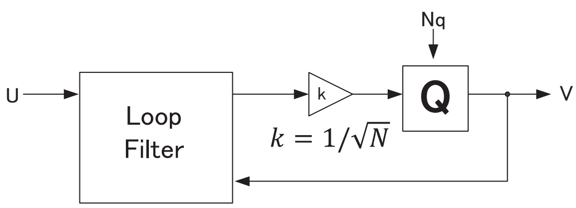


Figure 10 – Channel unit equivalent block diagram

$$V = \frac{k}{1+(k-1)z^{-1}} U + \frac{1-z^{-1}}{1+(k-1)z^{-1}} Nq \tag{3}$$

We have confirmed by simulation that the equivalent block diagram of Fig. 10 matches approximately the quantization noise spectrum of the proposed method (however, the gain k is $1/N$ only in the first-order system). In addition, the suppression characteristics of the quantization noise can be controlled by changing the order of the loop filter, as in the case of a normal ΔΣ modulator. In the proposed method, the system may become unstable in the second- or higher-order system, but the stability can be maintained by controlling the pole location of the loop filter as in the normal modulator. At that time, the transfer function shown from each channel is expressed by the following:

$$V = \frac{k \cdot STF_1(z)}{k+(1-k)NTF_1(z)} U + \frac{NTF_1(z)}{k+(1-k)NTF_1(z)} Nq \tag{4}$$

STF_1 and NTF_1 are transfer functions of the input signal and quantization noise when $k = 1$.

2.4 Drive Signal Combination

The proposed method can be used even if one side of the signal is a pseudorandom signal. Hence, the control signal that is changed according to the sound source is only one side, and advantages such as simplification of hardware and prevention of limit cycles can be obtained. Therefore, in this study, we examined the stability of the two drive methods, as described below. Method 1 is a method in which the X-axis direction is a random signal of M-sequence and the Y-axis direction is a control signal, as shown in 11(a). Method 2 is a method in which both the X- and Y-axes are used as control signals, and they are alternately quantized, as shown in Fig. 11 (b). For convenience, these control methods are herein named as one-dimensional and two-dimensional control, respectively. In these methods, the effective sampling frequency and information amount of the control signal are the same, and when the same loop filter is used, the spectrum after quantization coincides. Fig. 12 shows the spectrum of a third-order modulator in which the pole of NTF_1 is 0.93 in each method. The results in the configurations of (a) and (b) of Fig. 11 are indicated by “a” and “b”, respectively, in Figs. 12 and 13. The characteristics are highly consistent. Meanwhile, differences are observed in the range of pole locations that operate stably. Fig. 13 shows the spectrum when the pole location is 0.9. As shown, the two-dimensional control operates stably even at the pole location that becomes unstable when quantized by a one-dimensional control signal. Consequently, a better S/N can be obtained in the two-dimensional control. Therefore, although the transfer function as a filter is the same, the range of stable operation differs depending on the drive type.

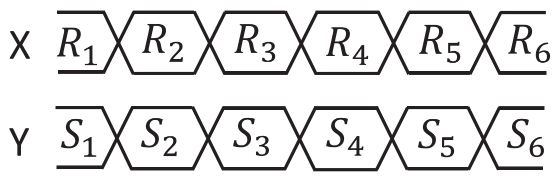


Figure 11(a) – Combination with random signal

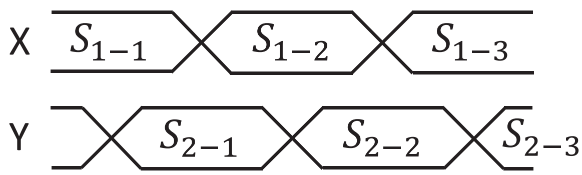


Figure 11(b) – Alternate quantization method

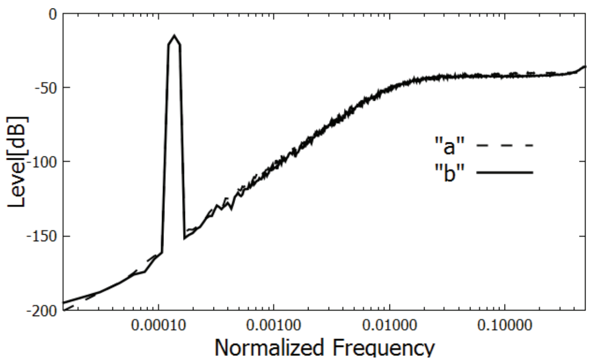


Figure 12 – Comparison of quantization results within a stable range (pole location = 0.93)

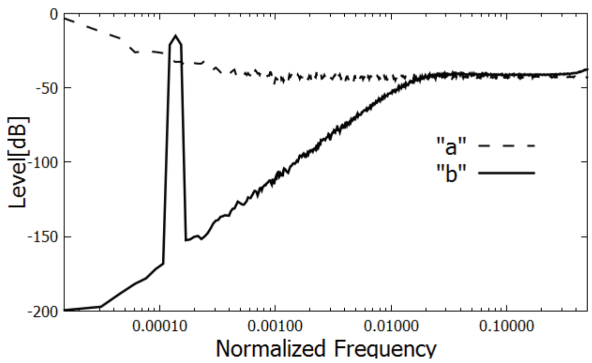


Figure 13 – Result of moving the pole (pole location = 0.9)

3. COMPARISON OF STABILITY BY DRIVE METHOD

3.1 Stability to input signals

In a normal ΔΣ modulator, the level of an input signal that operates stably is limited according to the peak of the frequency characteristic in the loop filter. Meanwhile, the proposed method is characterized by that the quantizer of the input signals are common, and that the stable operating input range will be determined by the input level for each channel and the entire system. Therefore, in the proposed method composed of four M-sequence signals and one control signal shown in Figs. 7 and 11 (a), the relationship between the location of the unstable pole and the input signal was confirmed by simulation. Fig.14 shows the levels of the input signals for which the simulation was performed. The numerical value of the level is normalized by $1/\sqrt{2N}$ to the quantizer output -1,1. Moreover, considering the limit cycle, the notation "0" is approximated by a minute input of 1/1000. The frequencies of the input signals are bin numbers 9 to 13 for the window length 65536, and the signals are different sine waves. The number of quantization bits is one. The poles of NTF_1 were slid and the values at which the system became unstable were compared. The results for driving points 4 to 64 are shown in Fig. 15. The value of the pole is shown as a normalized value between the value when all the inputs are 1 and that when all the inputs are 0. Although the input signals are different from each other, the unstable pole values show the same tendency for the group in which the sum of squares of the input signals is 2 (A,B,C) and the group in which they are 1(D,E). As described in Section 2.3, in the proposed method, each quantizer input can be regarded as whitened and added to each other. The results in Fig. 15 suggest that the stable input range is also determined by the sum of the input signal energy.

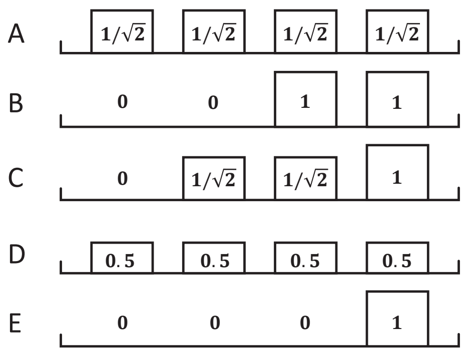


Figure 14 – Combination of input signal levels (one-dimensional control)

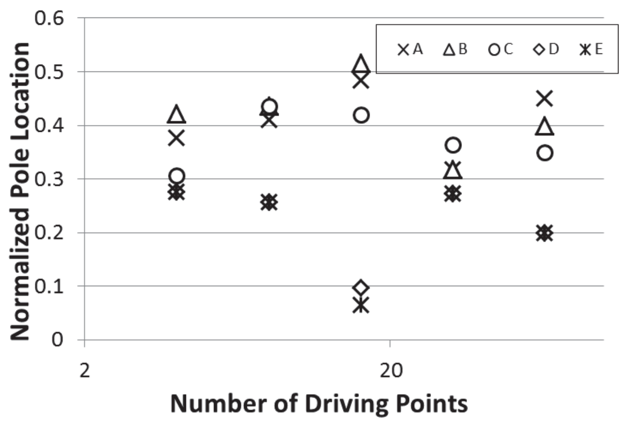


Figure 15 – Stable pole position with respect to driving points (one-dimensional control)

Meanwhile, simulations were performed in the case of alternate quantizing; as shown in Fig. 11 (b) , and is simulated with a 4 × 4 structure. The input channel is divided by 2 × 2, and similar to Fig. 14, a simulation is performed by inputting a sine wave with the amplitude value of the pattern shown in Fig. 16. The obtained minimum pole location for a stable operation is shown in Fig. 17. Even in the two-dimensional control, the pairs (A,B) and (C,D) in which the energy sums of the quantizer input signals coincide are well matched. It was suggested that the stable range was determined by the energy sum of the input signal in the two-dimensional control.

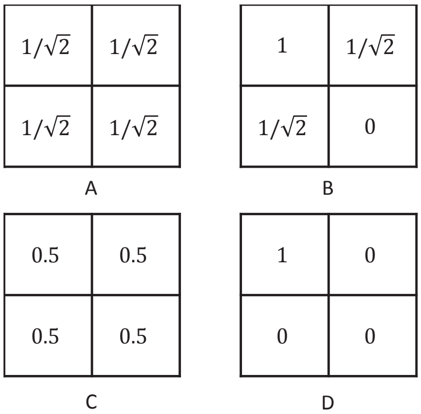


Figure 16 – Combination of input signal levels (two-dimensional control)

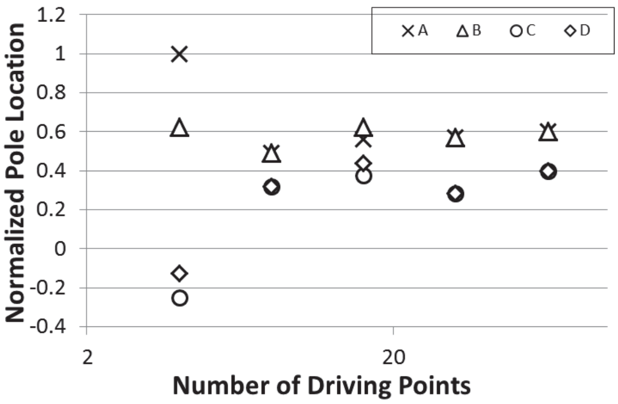


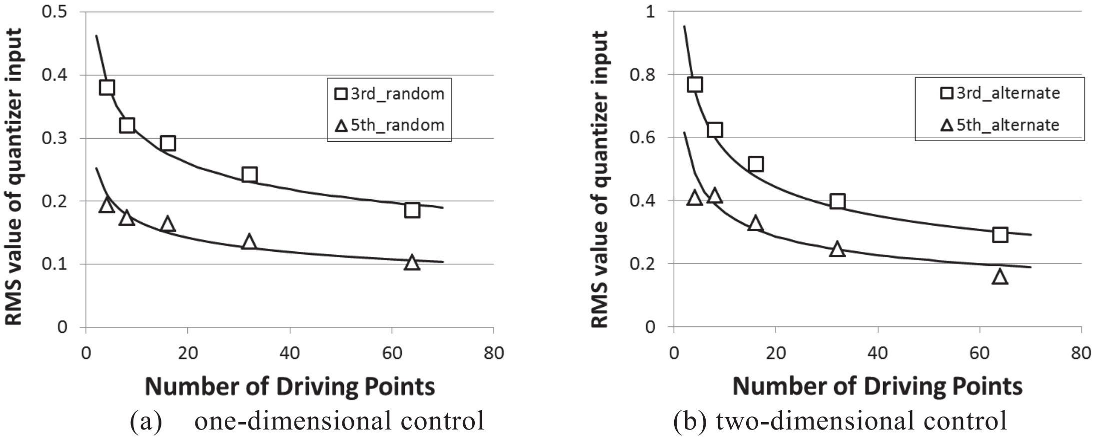
Figure 17 – Stable pole position with respect to driving points (two-dimensional control)

3.2 Differences in stability due to driving methods compared at quantizer input

The design of a normal ΔΣ modulator is performed by calculating the peak of the transfer function of quantization noise. Meanwhile, in the proposed method, as shown in Fig. 9 and Section 3.1, the quantization noise itself changes in according to the input of all channels. In addition to that, as shown in Section 2.4, although the transfer function of the system is the same, the range of stable operation differs depending on the drive type. Thus, in order to discuss stability, it is necessary to consider parameters including these terms that occur non-linearly. Therefore, we considered that the amount of feedback energy from the quantizer was different depending on the driving method, and compared the RMS value of the quantizer input and the stable operation range.

In the simulations, the input signal is a sine wave of amplitude $1/\sqrt{2N}$ with different frequencies in each channel. The locations of the poles of NTF_1 were reduced and the RMS values of the quantizer input at the limit of stable operation were plotted. The simulation to 4 to 64 ch was performed and an approximate curve was added. The results for the one- and two-dimensional controls are shown in Figs. 18(a) and 18(b), respectively. The approximate curve in the figure is shown below.
Third-order modulator in one-dimensional control: $0.55 \times N^{1/4}$
Fifth-order modulator in one-dimensional control: $0.3 \times N^{1/4}$
Third-order modulator in one-dimensional control: $1.2\times N^{1/3}$
Fifth-order modulator in one-dimensional control: $0.78 \times N^{1/3}$

The two-dimensional control can operate stably with a large quantizer input, thus implying that the stable operation range is wide. In addition, the results fit well to the order of $N^{1/4}$ in one-dimensional control and to the order of $N^{1/3}$ in two-dimensional control. Although the theoretical background of these values is a future subject, we could obtain an index indicating the difference in stability in each drive system. The transfer function to the quantizer input can be found by subtracting Nq from NTF in Eq. (4). Therefore, by obtaining an approximate curve, an appropriate pole location can be back calculated for the number of driving points.



(a) one-dimensional control (b) two-dimensional control

Figure 18 – Driving point vs. RMS value of quantizer input

4. CONCLUSIONS

We herein discussed the relationship between driving method and stability in our proposed MIDS modulator. We examined two driving methods: a driving method that quantized one dimensionally in combination with a random signal, and a two-dimensional driving method that quantized the X- and Y-axes alternately. As a result of simulation by the combination of multiple input levels, it was confirmed that the sum of energy of the input signal was related to the range of pole location for a stable operation in each driving method. In addition, by analyzing the RMS value of the quantizer input with respect to the number of driving points, the RMS value was approximated to the power curve specific to the driving method. By obtaining these approximate curves, the pole location for stable operation could be calculated with respect to the number of driving points, that is, the difference in stability between them was demonstrated.

In the proposed method, although the speaker required a multiplication output structure, the speaker array could be driven individually while using common wiring. Moreover, a passive structure could be constructed using a diode, a capacitor speaker, etc., and a “super multi-channel” speaker array could be created. The findings in this paper suggested that stability increased in the order of the power as the number of combinations of control signals increased. In the future, we would like to consider a method in which the two-dimensional quantization method is not performed alternately on the X- and Y-axes, but instead all points are collectively performed.

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REFERENCES

1. ACOUSTIC KEYWORD BOOK, The Acoustical Society of Japan ed., CORONA PUBLISHING, Tokyo, 2016. p. 194-195
2. Shigeto TAKEOKA. A Method of Driving Multi-channel System by Using Multiplication Outputs with Random Signals. IEICE Technical Report, vol. 116, no. 122, EA2016-16. July 2016. p. 45-49.
3. Shigeto TAKEOKA. Matrix Driving Method for Multichannel Loudspeaker using Multiplication-output and Delta-sigma Modulator with Multiple inputs. IEICE Technical Report, vol. 117, no. 328, EA2017-83. November 2017. p. 133-138.
4. Takeru SONOBE, Shigeto TAKEOKA. Generation of Wavefront by High Density Electro-dynamic Multiplication Output Loudspeaker Array Using Multiple Inputs Delta-sigma Modulator. IEICE Technical Report, vol. 118, no. 234, EA2018-56. October 2018. p. 13-19.
5. Naoki Yatame, Yasutaka Tamura et al. Edge-Connected 2 Dimensional Array Composed of Nonlinear Acoustic Devices. Japanese Journal of Applied Physics, vol. 41, 2002. p.3348-3353.
6. TAMARA G.KOLDA et al. Computation and Uses of the Semidiscrete Matrix Decomposition ,ACM Transactions on Mathematical Software, Vol. 26, No. 3, 2000. p.415–435 .
7. Takeshi KOIKE et al. Driving Edge-Connected array speaker for Semi Discrete Decomposition , Reports of the 2105 spring meeting the Acoustical Society of Japan, March 2015. p.595–596 .
8. Richard Schreier, Gabor C. Temes, Understanding Delta-Sigma Data Converters, Wiley-IEEE Press,2004