DIGITAL RECORDING AND REPRODUCING TECHNIQUE WITH THIN FILM HEAD FOR DIGITAL AUDIO TAPE RECORDER

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"Digital Recording and Reproducing Technique with Thin Film Head for Digital Audio Tape Recorder"

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Abstract

We have developed a 16-channel digital audio tape recorder employing the 1/4-inch tape. Its features are tape saving, simplified tape handling, application of the same of head, tape and tape running mechanism as those used for the master recorder.

This development became possible owing to application of the thin film magnetic head enabling to record and reproduce short wave signals and having 20 heads in a 1/4-inch width, the new driving method suited to the thin film magnetic recording head, and reproducing signal equalization. Applying these new techniques, we examined the recording and reproducing characteristics of thin film magnetic head, and obtained the results described below.

1. The power consumption of thin film recording head having a reduced number of turns was decreased to 1/4 or below.

2. The recording head crosstalk was reduced by about 20 dB.

3. The dependance of overwrite modulation characteristics upon wavelength was revealed.

4. The reproducing signal peak shift in the case of recording and reproducing by high density recording modulation ensuring the shortest recording wavelength of about 2 μm was revealed, and it was reduced to 1/10 or below.

This paper discusses these items.

Introduction

As we are entering upon the age of digital audio tape recorder, the digital audio equipment for studio has become more important for production of digital master source of DAD (Digital Audio Disc) or production of master source of conventional analog disc. Moreover, as the PCM broadcasting which is designed to transmit the pulse-code-modulated audio signals through the direct broadcasting satellite is being developed, the digital audio equipment is becoming more important also for production of master source for broadcasting. The authors announced the digital audio tape recorder and electronic editor already at the 66th AES Convention in 1980 [1]. Subsequently, the digital audio mixer [2], digital preview unit, and digital reverbrator [3] were announced. We executed the field test of these audio equipments in the recording studio so as to improve their performance and reliability. As a result, it was keenly required to develop the small and light digital multichannel recorder having more available channels.
To realize the small digital multichannel recorder having more channels, it is necessary to increase the track density and liner recording density. The track density can be increased by using the thin film magnetic head. However, for increase of linear recording density it is necessary to realize the short wave recording and reproducing. If a multichannel recorder enabling to use the same 1/4-inch tape as that used for the master recorder is realized, the tape consumption is reduced, tape handling is simplified, and equipment size is decreased as compared to the conventional types, and furthermore another advantage is also obtained, namely it is possible to use the same head, tape and tape running mechanism as those used for the master recorder. For the purpose of realizing this specification we developed a thin film magnetic head having 20 heads in 1/4-inch width, and developed a 16-channel digital audio tape recorder of one track/channel system employing the above-mentioned head and 1/4-inch tape. The digital audio tape recorder for professional use also requires replacement of program source. Consequently, the unified standard such as tape format is important. The sampling frequency of 48 kHz and 16 bit quantization have been approved at AES Digital Audio Technical Committee. But there are remained many items to be decided, track format, signal format, I/O interface and so on. Our development discussed in this paper focused on digital recording and reproducing technique and was based on the basic specification as follows:

Sampling frequency: 48 kHz
Quantization: 16 bits
Redundancy: 33%
Required recording data rate: 1.152 Mbps per audio channel

If the density ratio of recording modulation is 1.5 and tape speed is 76.2 cm/s, the shortest recording wavelength is 1.98 μm.
In our development we examined the recording head driving method, reduction of crosstalk, overwrite modulation characteristics, and suppression of reporducing signal peak shift so as to realize the steady recording and reproducing of such short wave with the aid of thin film magnetic head.

Outline of Thin Film Magnetic Head

The recording head [4] has been published in AES '66 Convention paper 1636. Its operating principle is the same as that of conventional ring head. Namely, the coil wound around the magnetic core is energized to induce a magnetic flux in the magnetic core, due to which a magnetic field is formed in the magnetic gap. The number of coil turns is 3. Figure 1 is its perspective veiw. To form a head, coil is wound around the grooved structure planner magnetic substrate whose groove is filled with nonmagnetic material so as to reduce the magnetic leak between the magnetic substrate and the magnetic film, thereby improving the efficiency.

The reproducing head is the MR reproducing head which utilizes the magnetoresistive (MR) effect of the ferromagnetic thin film ensuring relatively high output at low relative speed with respect to the recording medium. This MR reproducing head excels also in crosstalk characteristics. The crosstalk of the newly developed head was lower than noise level. Because the MR effect of ferromagnetic thin film gives usually nonlinear change of specific resistance when the external magnetic field is changed, the thin film magnetic head must be used in the linear range by applying the bias magnetic field. The recently developed head features that the magnetic unisotropy is given to the MR film to impress the bias magnetic field. To give the magnetic unisotropy, fine strip ruggedness (hair line) is formed on the MR film. Namely, we have developed the hair line bias type (HL) MR head [5]. Figure 2 shows the structure of the HLMR head. The hair line formed on the substrate surface is transcribed to the MR film through the gap insulation film, and the magnetic unisotropy of the film depends on the depth and direction of hair line pitch. Accordingly, the magnetic thin film and conductor film are not provided as bias impressing means in the gap unlike the conventional MR head, the gap width is reduced, and short wave reproducing is facilitated. Figure 3 shows the appearance of the head (recording head and reproducing head).

Driving Method of Thin Film Magnetic Recording Head

Because of reduced number of turns the thin film recording head requires increased recording current to obtain the same recording level on magnetic tape as that of conventional head. This results in increase of power consumption of the recording head and increase of heating. The driving method ensuring power saving is pulse train current recording method [6]. The pulse train current waveform is shown in Figure 4. The waveform parameters are pulse period t and pulse width d. We measured the optimum values of recording current, reproducing output and overwrite modulation noise at various values of the parameters.

Figure 5 represents the optimum recording current vs. reproducing output when the pulse period t is changed at d = t/2 (pulse duty of 50%) whereas Figure 6 represents the same relation when the pulse width d is changed at given values of pulse period t. It has been revealed that there is not difference in reproducing output between rectangular wave recording and pulse train recording. However, the optimum recording current tends to increase as the pulse width is reduced (pulse frequency is increased, and the pulse duty is lowered).

For the purpose of compairing the overwrite modulation characteristics we attempted to overwrite the signal of period 1 ℓ on the signal of period 2 ℓ at the optimum recording current for rectangular wave and pulse train wave. The obtained result is plotted in Figure 7. The pulse width is d = t/2. The overwrite characteristics of the pulse train recording is superior to that of the rectangular wave recording.

Thus, the pulse train recording does not differ from the rectangular wave recording in reproducing output and features improved overwrite modulation characteristics as compared to the rectangular wave recording. However, the overwrite modulation characteristics tend to lower as the pulse train period is decreased. When the pulse train pulse width is reduced, the current amplitude increases remarkably, due to which the influence of impedance of head and head wiring caused a problem. With due regard to these problems and the simplification of circuit composition we adopted the pulse width d = t/2. The pulse period must be equal to 1/N (where N is integer) of signal period. To realize the one track/channel system, it is necessary to adopt the high density recording modulation (density ratio is 1.5). In this case the minimum transition interval of modulation signal is set to 1.5 T (where T is bit period), and increment is 0.5 T. Taking the above-mentioned into consideration, we adopted the pulse period of 0.5 T. It conforms to the pulse period of $\ell/6$ in Figure 5 and Figure 7. Since the recording current amplitude is almost equivalent to that of rectangular wave, and the pulse duty is 50%, the recording current has been reduced to about 1/2. As a result of this, the power consumption of head has been reduced to 1/4, and head heating can be suppressed. Moreover, the overwrite modulation noise has been also improved.

Reducing the Crosstalk of Recording Head

The recording head has been highly integrated so as to increase the track density, hence there exist some influences of adjacent heads. Especially, in the case when the adjacent heads function simultaneously, crosstalk may occur. As shown in Figure 4, the pulse train current waveform has a halt period during which no current flows through the head. If the head of the adjacent track is put into operation during this period, the crosstalk which may occur during simultaneous operation of heads will be reduced.

We recorded the signal of transition interval of 1.5 on the track n, and the signal of transition interval of 3T on the tracks n-1, n-2, n-3, n+1, n+2, and n+3, using the three different pulse train current phases (A, B, C) as shown in Figure 8. When the 1.5 T signal of track n was reproduced subsequently, the signal conponent of 3T was observed in the reproducing signal. The pulse train current phase (A) corresponds to the case when current passes through all heads simultaneously. On track n, there occurs crosstalk from track n-1, n-2, n-3, n+1, n+2, n+3. The extent of improvement of cases (B) and (C) based on the crosstalk level in the above-mentioned case is shown in Figure 9. In the case of pulse train current phase (B) the crosstalk from the tracks n-2 and n+2 occurs on the track n, but the crosstalk level in this case is reduced by 19.5 dB as compared to (A). In the case of (C) the crosstalk from the tracks n-3 and n+3 occurs on the track n, but the crosstalk level is reduced by 4 dB as compared to (B). In the case of (B) where the pulse train current phase is varied between the adjacent tracks, sufficient improvement is attained, and the circuit composition is simple.

Overwrite Noise Characteristics

The multichannel recorder requires sync recording and punch-in-out functions. To realize these functions, the overwrite modulation characteristics are important. Substantially, the digital recording is saturated recording. Consequently, if recording is done ideally, preceding signal does not remain. However, since the recording state of some recording media and recording head depends on wavelength, the remaining component of already recorded signal may appear. With the recording modulation having a density ratio of 1.5, many transition intervals appear. Therefore we examined the overwrite modulation characteristics for the combination of them. The obtained result is plotted in Figure 10. The recording current is pulse train current which is set to $d = t/2$, $t = T/2$. The signal period for the shortest recording wavelength is 3T (transition interval is 1.5T). Although the overwrite modulation characteristics vary insignificantly according to type of tape, the largest overwrite noise occurs when overwrite is made on the signal of wide level transition interval (5T). Accordingly, it is better to apply the recording modulation whose max. transition interval is reduced as far as possible.

Characteristics of Reproducing Signal and Its Equalization

Figure 11 shows the isolated pulse of MR reproducing head which is obtained when the unit step signal is recorded. The formula (1) is conventionally applied as an approximate formula for the isolated pulse. This formula gives the Lorentz waveform which is shown in Figure 12.

$$g(t) = \frac{1}{1 + \left(\frac{2t}{W_{50}}\right)^2} \qquad (1)$$

where W_{50} is half width.
In the case of high density data recording or reproducing the parameter W_{50} becomes relatively larger as compared to the flux reversal interval, and the adjacent reversals of magnetic fields interfere with each other, thereby causing peak shift, namely deviation of peak position of reproducing signal. The peak shift can be determined by superposing the isolated pulse. The peak position corresponds to the level transition position of data. Consequently, if the peak position deviates, exceeding the detecting window width when the data modulated for recording is demodulated, it cannot be demodulated correctly to original data. Accordingly, it is necessary to reduce the peak shift. For this purpose many equalization methods have been proposed. To examine these methods, the above-mentioned Lorentz waveform is commonly used. However, the isolated pulse of MR reproducing head has a DC offset at the leading edge side as shown in Figure 11, and the positive and negative pulse peak values vary, resulting in waveform differing from the Lorentz waveform. Hence, the reproducing characteristics seems to be different. To decide the equalization method suited for compensation of reproducing characteristics of MR reproducing head and to establish the design principle of equalization circuit, we simulated the isolated pulse of MR reproducing head, analyzed the harmonics, and examined the peak shift.

From the isolated pulse of MR reproducing head which is shown in Figure 11 we read the half width, leading edge DC off-set value and positive and negative pulse peak value representing the features of reproducing waveform as shown in Figure 13, and simulated the isolated pulse by modifying the Lorentz waveform. Thus obtained 6 waveforms are shown in Figure 14. Of all 6 isolated pulses, S-I is really Lorentz waveform, whereas S-VI most resembles the actual waveform. Next, we determined the waveform of repetition of 3T (twice the shortest recording wavelength) by superposing, and determined the second and third harmonics of fundamental wave by Fourier transform of the thus obtained composite wave. The obtained result is shown in Table 1. As evident from Table 1, the waveforms whose second harmonic increases remarkably as compared to S-I are S-V and S-VI, and S-IV shows an insignificant increase. Hence, it is evident that the second harmonic increases if positive and negative pulse forms differ from each other.

We made three types of repetition pattern of 1.5T/4T, 1.5T/4.5T and 1.5T/5T by superposing, and determined their peak shifts. The obtained result is shown in Table 2. S-II features that each of three types of repetition pattern gives increased peak shift. It is evident that the peak shift depends on half width. Based on the results of harmonics analysis shown in Table 1 and the peak shift shown in Table 2 we concluded as follows.

(1) The second harmonic of reproducing signal (repetition of 3T) of MR reproducing head grows by 10 dB or so as compared to ideal waveform such as Lorentz waveform.
(2) The above-mentioned second harmonic does not affect the peak shift.
(3) The peak shift depends on half width.

Based on the consideration described above, we adopted the cosine equalizer [7] which ensures easy circuit composition, does not require control of the group delay characteristics and allows the half width to be reduced. The transmission function of the cosine equalizer is written in the following form:

$$G(f) = 1 - K\cos 2\pi f\tau \qquad (2)$$

where

K: gain
τ: delay time

This cosine equalizer circuit can be easily realized with the circuit composition shown in Figure 15. As evident from the formula (2), the equalization transmission characteristics can be changed by changing K and τ. We made simulation for the three types of repetition pattern of 1.5T/4T, 1.5T/4.5T and 1.5T/5T whose peak shift increases. Figure 16 shows how the peak shift is reduced by changing K and τ (only for 1.5T/4.5T). As a result of simulation it has been revealed that the peak shift at $K = 0.8$ to 0.9 and $\tau = 700$ nsec is reduced below 1/10 as compared to the case where equalization is not executed. Actually, we made a circuit having the composition set to $K = 0.8$ and $\tau = 700$ nsec to execute equalization. Figure 17 represents the obtained equalization waveform.

Conclusion

As a result of examination, it became possible to realize the steady recording and reproducing of digital data by high density recording modulation (density ratio is 1.5) owing to application of the thin film magnetic head which has 20 heads in 1/4-inch width and is capable of recording and reproducing the short wave. So we developed the 16-chaneel digital audio tape recorder using 1/4-inch tape. Figure 18 is its appearance view.

For further wide spread of the digital audio equipment it is necessary to ensure easy replacement of program source and easy mutual connection between equipments. Accordingly, the unified standard is necessary.

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References

(1) K. Sadashige and H. Matsushima, "Recent Advances in Digital Audio Recording Technique", AES 66th Convention, No.1652 (K-5), May, 1980.

(2) N. Sakamoto et al., "Digital Equalization and Mixing Circuit Design", AES 70th Convention, No.1809 (I-6), Oct. 1981.

(3) N. Sakamoto et al., "Digital Audio Reverberator", AES 70th Convention, No.1810 (I-7), Oct. 1981.

(4) K. Kanai et al., "Thin Film Tape Heads for PCM Recorders", AES 66th Convention, No.1936 (J-2), May, 1980.

(5) H. Yohda et al., "Hairline bias MR head", IECE JAPAN, MR82-36, 1982.

(6) R.K. Richards, "Digital Computer", D. Van Nostrand Company INC. 1957.

(7) T. Kameyama et al., "Improvement of Recording density by means of cosine equalizer", IEEE. Trans. Mag, MAG-12, No.6, Nov. 1976.

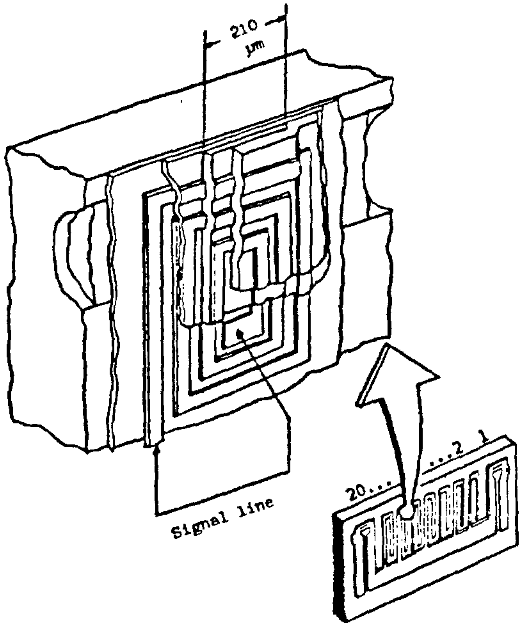

Fig.1. Perspective view of a thin film recording head on a magnetically grooved substrate

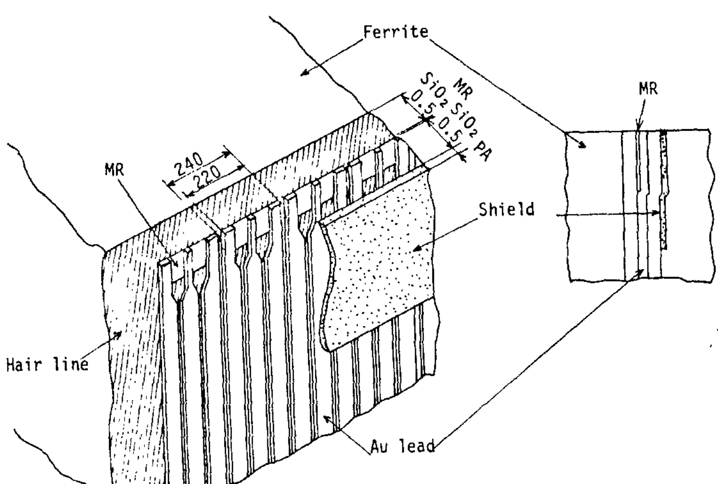

Fig.2. Structure of the MR head

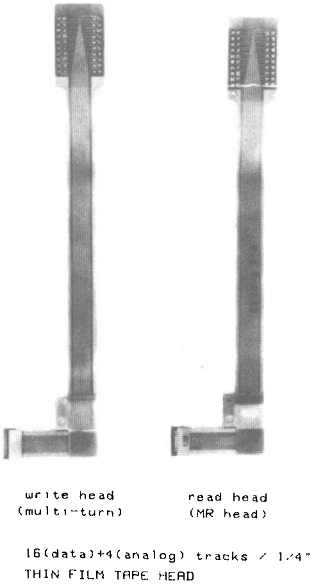

Fig.3. The appearance of the thin film head

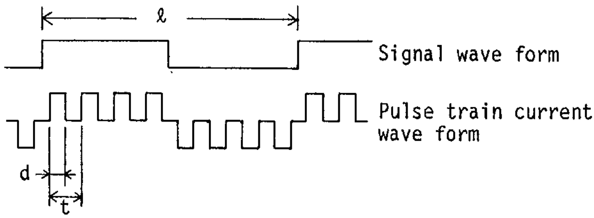

Fig.4. Pulse train current wave form

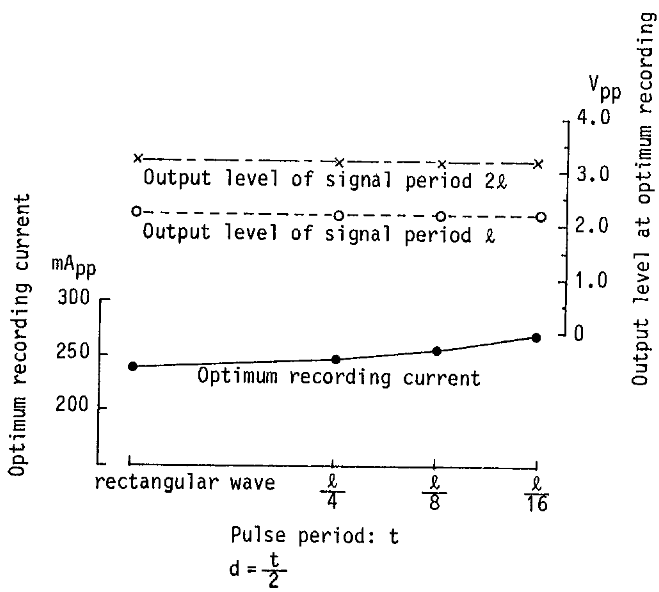

Fig.5. Optimum recording current vs. pulse period

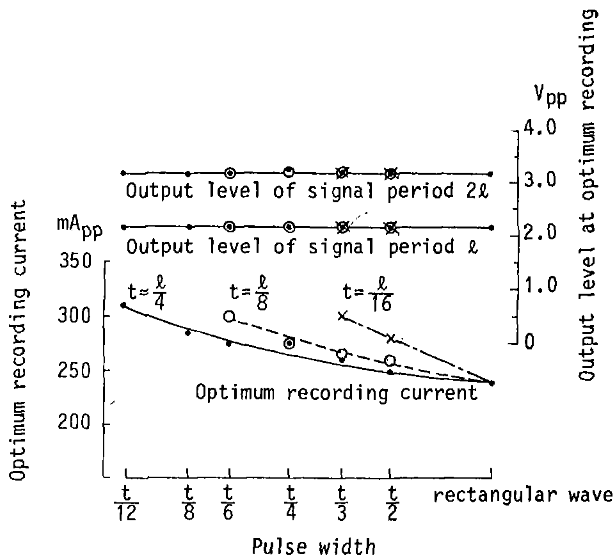

Fig.6. Optimum recording current vs. pulse width

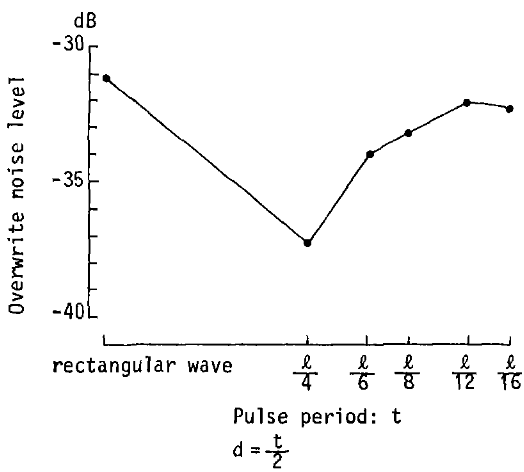

Fig.7. Overwrite noise level vs. pulse period

Track No.	Signal	Pulse train phase (A)	(B)	(C)
n-3	3T	ϕ_1	ϕ_2	ϕ_1
n-2	3T	ϕ_1	ϕ_1	ϕ_3
n-1	3T	ϕ_1	ϕ_2	ϕ_2
n	1.5T	ϕ_1	ϕ_1	ϕ_1
n+1	3T	ϕ_1	ϕ_2	ϕ_3
n+2	3T	ϕ_1	ϕ_1	ϕ_2
n+3	3T	ϕ_1	ϕ_2	ϕ_1

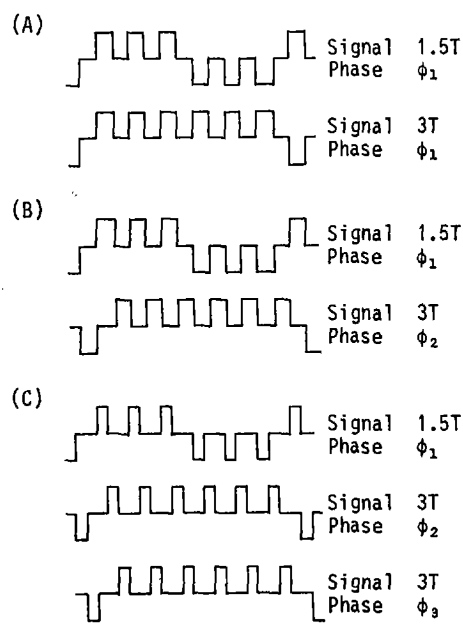

Fig.8. Schema of recording head current

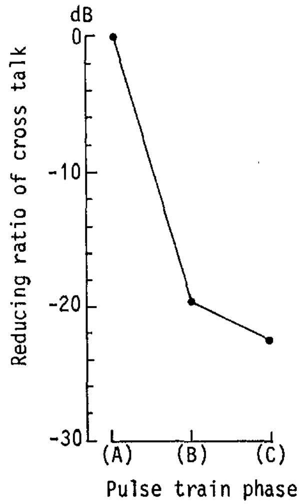

Fig.9. Improvement of cross talk

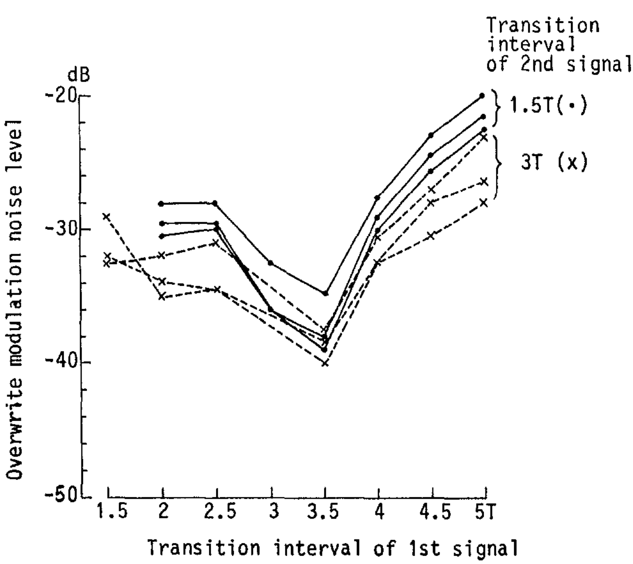

Fig.10. Overwrite modulation noise level vs.
Transition interval

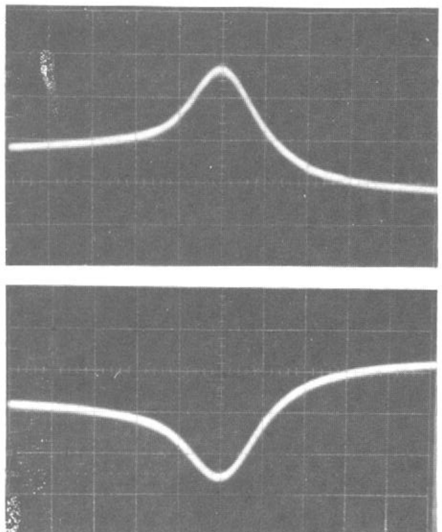

Fig.11. Reproducing isolated pulse
(0.2v/div,1μsec/div)

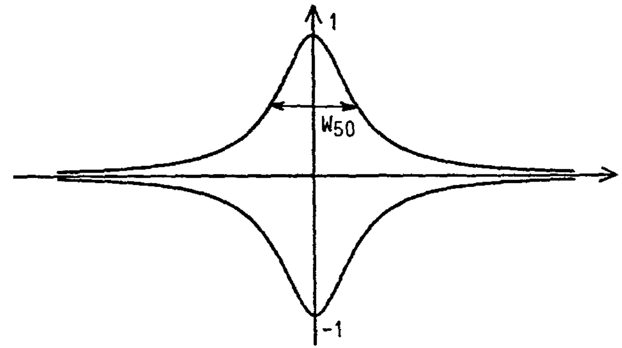

Fig.12. Lorentz wave form

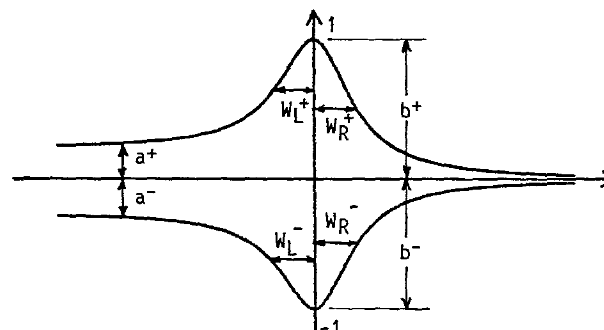

Fig.13. Parameter of the isolated pulse

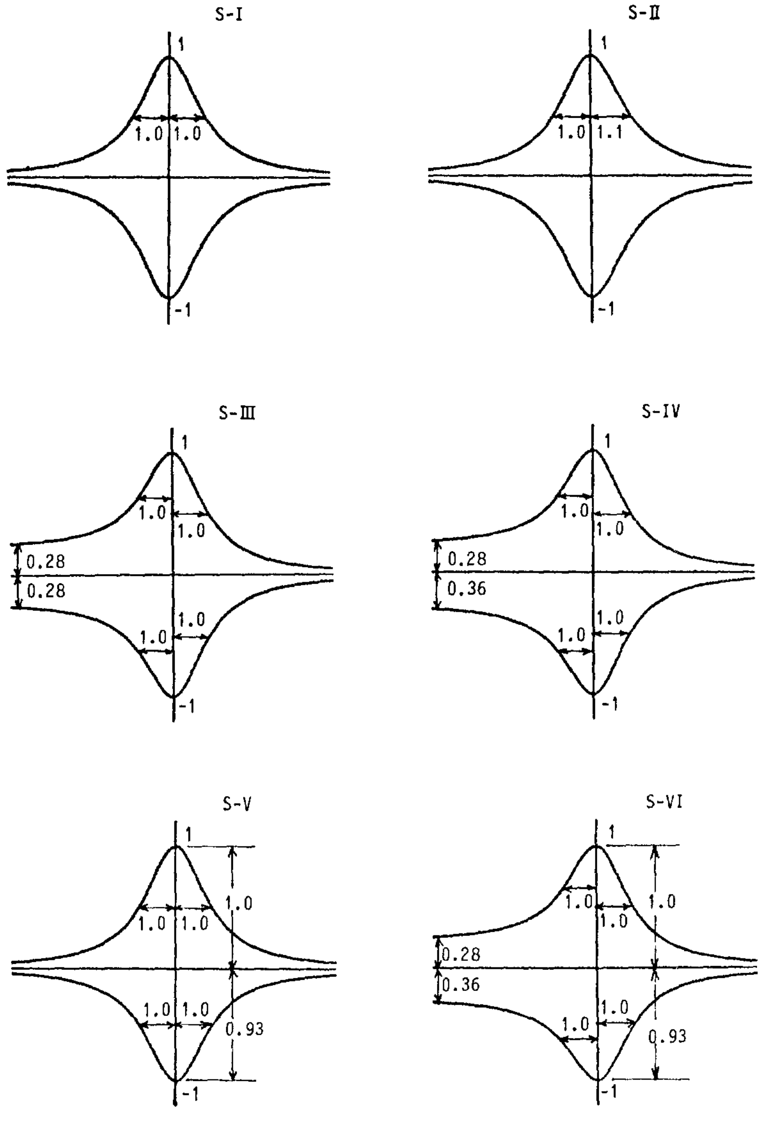

Fig.14. Simulated wave form

Table 1 Harmonics spectrum of the signal 3T

Wave form / Harmonics	S-I	S-II	S-III	S-IV	S-V	S-VI
1st [dB]	0.0	0.0	0.0	0.0	0.0	0.0
2nd [dB]	-48.1	-48.4	-47.7	-44.2	-36.4	-34.8
3rd [dB]	-20.4	-21.4	-20.4	-20.3	-20.4	-20.3

Table 2 Peakshift characteristics

Wave form	S-I	S-II	S-III	S-IV	S-V	S-VI
1.5T/5T	0.348	0.387	0.347	0.337	0.349	0.339
1.5T/4.5T	0.345	0.386	0.344	0.334	0.345	0.335
1.5T/4T	0.327	0.363	0.326	0.315	0.327	0.318

(x T, T; bit length)

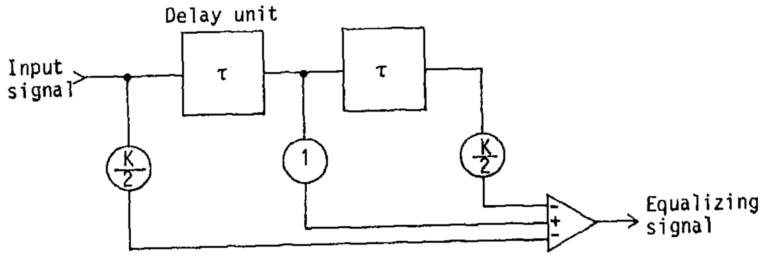

Fig.15. Cosine equalizer

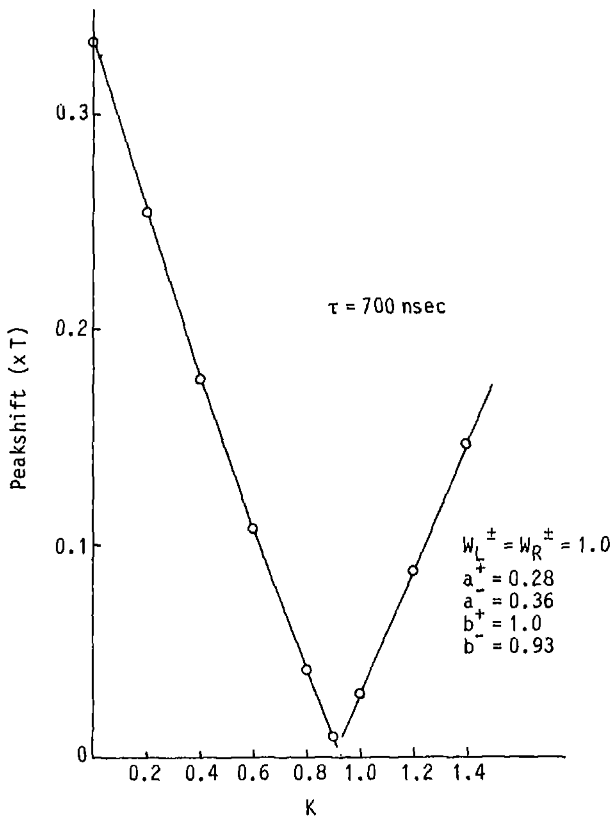

Fig.16. Peakshift vs. K

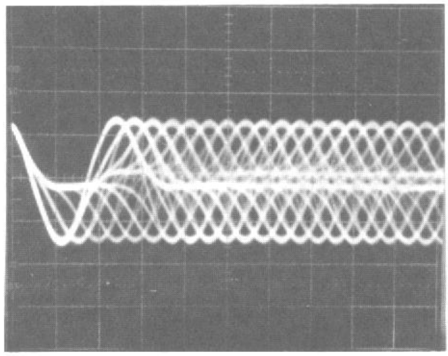

Fig.17. Equalized reproducing signal
(0.2/div,1μsec/div)

Fig.18. The appearance of the 16-channel digital
audio tape recoder and Remote control box