Effects of fluctuation in sound transmission on objective sound fields and subjective evaluations

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EFFECTS OF THE FLUCTUATION IN SOUND TRANSMISSION ON OBJECTIVE SOUND FIELDS AND SUBJECTIVE EVALUATIONS

（室内音響伝搬におけるゆらぎの物理的および心理的効果に関する研究）

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Preface

This report is a dissertation for the doctor of philosophy degree to be submitted to Graduated School of Science and Technology, Kobe University.

The report indicates that a factor, which we call "fluctuation, time variant factor", is significant in sound field although previously it had not been recognized as such. The author tried to reveal the existence of sound transmission change, explain that the acoustical model include time varying factors and evaluate the effects of the fluctuation on subjective preference that is one of the most important subjective judgments in room acoustics.

The author wishes to thank Professor Yoichi Ando of Kobe University for his kind guidance and encouragement.

All the responsibilities for whatever errors which might occur on following pages are due to the author.

YASUTAKA UEDA

Tsukuba, Ibaraki
Jun, 1997

List of symbols

$p(x)$	:	Probability function of x
$\overline{p_2}$	:	Mean squared amplitude
σ	:	Standard deviation
δ	:	Delta-function
$P(x)$	:	Cumulative density of x
$p(t)$	:	Sound pressure of t
R_n	:	Relative amplitude of each reflection
t_n	:	Delay time of each reflection
α_n	:	Change interval of delay time change
β_n	:	Change pattern of the delay time
$< >$	:	Mean
ACF	:	Auto correlation function
τ_e	:	Effective duration of ACF, time delay for the rectified ACF envelope dampened to 0.1.
Δt_1	:	Delay time of the first reflection
RT	:	Reverberation time
IACC	:	Interaural cross correlation
LL	:	Listening level
$[\Delta t_1]_p$	:	The most preferred delay time of the first reflection
$[\Delta t_1]_{pm}$	:	The most preferred delay time of the first reflection with modulation
Δ	:	Fluctuation interval of delay time for the first reflection sound
Δ_{sin}	:	Δ at JND obtained sine wave as the modulation pattern
Δ_{oct}	:	Δ at JND obtained oct-band noise as the modulation pattern
Δ_{SPL}	:	Changing span in SPL
JND	:	Just noticeable difference
Mf	:	Modulation frequency
SV	:	Scale value of subjective preference

MM	:	Modulation method
MP	:	Modulation pattern
SL	:	Signal level of sound stimulus
Motif A	:	Royal Pavane composed by Gibbons, anechoic music
Motif B	:	Sinfonietta composed by Malcolm Arnold, anechoic music

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CHAPTER I

INTRODUCTION

1.1 General preface

Essentially, sound which surrounds us is in accordance with time varying system that its intensity, direction, spectrum and frequency are changing with time. The fluctuation called "yuragi" in Japanese, is widely known and has been thought to affecting on psychological attribute. The researchers have noticed that this time variant factor showed be incorporated into the creation of more preferable sound field. But its quantitative effects on human beings are yet to be clarified. In the study of the environmental and acoustical field, it become necessary to investigate effects and allowances range of this fluctuation.

In this report, this fluctuation was regarded as one factor of time variant systems in room acoustics. The fluctuation of sound pressure level was considered to be the specific object and was examined from the standpoint of room acoustics. Physical and Psychological approaches relating this time variant system was studied.

The fluctuation of amplitude was examined statistically in order to find out the mechanism of its occurrence. It was assumed that time variant system would take effect on subjective preference which was one of the most important subjective factors in room acoustics. So, a series of psychological tests was made to clarify its effects.

1.2 Previous investigations and studies

1.2.1 Physical investigations of fluctuation

In the field of room acoustics, there are not so many studies relating fluctuations or modulations because sound fields have been designed based on diffuse sound fields where acoustical energy is ideally proliferating.

While in outdoor sound propagation, fluctuation and excess attenuation of sound pressure level (SPL) caused by phase changes and interference of waves have been examined in different ways and means, it has been said that the movements of air flow, temperature gradients and air absorption effect on out-door sound propagation. Previous researchers tried to solve strict solution or to use boundary element method (BEM)[58)] in order to predict characteristics of sound propagation. But these methods can not deal with the meteorological conditions. It was also said that the quantitative effect of each factor was hard to predict, because such meteorological factors were so dynamic. Mainly effects of air turbulence and temperature gradient in meteorological parameters have been examined in out-door sound propagation.

It seems that there are 3 kinds of calculation methods taking account of boundary conditions and meteorological factors. They are,

1) Ray tracing solution: The calculation method based on geometrical theory which regards the sound propagation as optical ray (R. J. Thompson, 1974[50)], 1975[48)]; T. F. Embleton, 1974[59)]; G. A. Daigle, 1979[12),13),14)]). They showed approaches, that statistical theory was introduced into upper geometrical theory.
2) Fast field program: The calculation method using the fast Fourier transform in order to solve the wave equation (M.West et al, 1991[36)]).
3) Parabolic equation method: The calculation method based on Helmholz equation dealing with only progressive wave (M.West et al, 1992[37)]).

Many field studies were experimentally performed (P. H. Parkin, 1965[43)], 1967[44)]). Scale model analyses were also utilized in the systematic way (H. Tachibana, 1976[21)]; R. Dejong, 1976). Concerning with effects led by temperature gradient from ground level to sky, most studies have been based on the snell's low theory. In a similar way, there were also field experiments[43),44)], applying many composite meteorological factors (A. R. Kriebel, 1972). Sound pressure level was changed by the meteorological factors at the propagation length more than several scores meter. The standard deviation of sound pressure level fluctuation is about 2 ~ 3 dB at high frequency range. The reflection coefficient of the ground was also replaced by meteorological factors. As dried grassland was acoustically soft, and rain made land hard[54)], these kinds of studies were all followed by the complicated meteorological factors which could not be identified one by one.

The statistical approaches, which were utilized in out-door sound propagation[28),39),62)] and fundamental acoustical issues relating time[26),29),31),32)] were helpful ways to examine this problem. Ingard and Maling (1953[60)], 1964[61)]) reported the sound propagation in a turbulent medium in a statistical way. Waterhouse (1969)[45)] showed statistical properties of reverberant sound fields. In other scientific fields, Adachi explained the statistical properties of electromagnetic propagation in terms of fading. Maisel (1972)[30)], Cramer (1947)[19)] instructed statistics and random processes mathematically.

In the field of musical acoustics, it was reported that the time structure of sound (like as time and shape of sound level) was important to simulate sound of a musical instrument (Rasch, 1978)[52)].

At the development process of moving pursue system utilizing ultrasonic waves, it was reported that air current produced by air-conditioning system led this system to error (Mita et al).

From previous studies connecting time varying system, that was fluctuation or modulation, it could be presumed most studies have been done only in outdoor sound propagation.

1.2.2 Psychological investigations of temporal change.

Many studies have been made concerning with the relationship between time information and psychological and/or physiological attributes. Followings are the brief of previous investigations in terms of the usage of temporal information in auditory system. The physiological reactions from the temporal information have been examined from the different point of view. Many researchers have investigated the relationship between loudness and signal duration for pure tone over a wide range of frequencies and duration[24)]. It was supposed that the energy of sound stimulus was integrated using temporal window of auditory system (Exner, 1876[11)]; Houghes, 1946[25)]; Garner, 1947[15)]).

From the experiment of the relationship between the modulation span and the subjective detection, subjects could detect sound pressure level fluctuation, when the modulation span in SPL was 1.5 dB at 20 dB of signal level (SL), 0.7 dB at 40 dB of SL and 0.3 dB at 80 dB of SL, in the case of 1.0-Hz pure tone as a source signal (Riesz, 1928). The stimulus signal with amplitude modulation (AM) and frequency modulation (FM) were used in order to examine the utilization of the phase information in the auditory system (Zwicker, 1952, 1965a[66)], 1965b[67)]; Schorer, 1986[55)]). But at present time it is not clear whether this finding can be generalized to the perception of suprathreshold level of modulation, or the other aspects of our sensitivity to phase.

It was reported that the modulated signal could be easily detected rather than that without modulation by using the temporal information of auditory filter. It meant that these usages of temporal information were taken to be one of cues for the mechanism of cocktail party effect.

In the binaural studies, the relationship between sound image following and changes in the location of stimuli was also investigated to perceive movement of a sound source (Perrott, 1977[40)], 1989[41)]; Grantham, 1978[18)], 1979[17)], 1986[16)]).

In all, it was supposed that there was temporal resolution (or acuity) and temporal summation (or integration) in the signal detection process, the latter was utilized to the auditory system to add up information over time to enhance the detection of discrimination of stimuli. In the studies of temporal integration, because as changes in the time pattern generally lead to changes of its magnitude spectrum simultaneously, white noise or sound stimulus with masker has been used. Authors tried to make the sound source with modulation at the time of psychological experiments.

Concerning effects of temporal factor on subjective preference, the sound combination that has similarity in temporal pattern of nerve excitation, increased the scale value of subjective preference (Mayer, 1898[33)]; Boomsliter and Creel, 1961[7)], 1963[8)]). They suggested that the simple rations of melody might be favored, because they are neural codable as combination, by processes that were inherent in the auditory neural system. They regarded the auditory neural system as like the developing system of auto- correlation network. But data of physiological aspects as like brain waves were not found in this article.

When frequency, intensity, sound image (location) and spectrum of objective sound change slowly, the change was regarded as continuous and smooth rather than abrupt. Whereas a sudden change leads that a new sound source has been activated. So this tendency was named the good continuous principal (Albert and Gary, 1973; Sturges, 1974[57)]). Albert et al found that when a rapid repeating cycle of alternating high and low tones was presented under the discrete condition, transitions between tones were abrupt. And under the ramped condition, successive tones were connected by frequency glides. The facts obtained from these experiments did not exceed the general attributes. They left still uncertain points in the relationship between time variant system and subjective judgments, especially preference. The conditions could not clear, which would increase the scale value of subjective preference. There is a little study which have investigated the relationship between subjective preference and temporal change. It would be desirable to make out some idea in order to present stimulus sound with modulation.

1.3 Aim of this study

With respect to outdoor sound propagation, time variants such as fluctuation or modulation of sound pressure level were taken into consideration in many studies. Issues of room acoustics have been discussed on the basis of steady state sound fields, and time varying factors have been mostly ignored.

However time varying objects of room acoustics that are caused by the movements of players and audiences and the environmental changes (temperature gradients or air movements) could be thought to effect sound transmission. SPL fluctuation has been produced already in the gymnasium by air current coming from air conditioner. It was assumed that SPL fluctuation was caused by changes in sound transmission of room, and would contribute to increase the scale value of subjective preference.

In order to make the effects of this fluctuation clear, the study was conducted from physical and psychological stand points.

As regards physical aspects, following analyses were made.

--- The statistical analysis of SPL fluctuation to determine the specific shape of distribution.

--- The proposal of acoustical model including time varying factors and the examination of its appropriate.

As regards psychological aspects, following experiments were conducted in order to observe effects of fluctuation on subjective judgment.

--- Experiments relating to differential threshold for time varying sound field.

--- Experiments relating to the relationship between subjective preference and time varying sound field.

CHAPTER II

THE MECHANISM OF TIME VARIANT SOUND FIELD

2.1 Preface

More and more buildings with large indoor spaces have been built in recent years. The air conditioning systems used in such buildings have also increased in size, and it is supposed that they has been leading to significant changes in the physical environment.

In this chapter, effects of air currents produced by an air conditioning system on sound transmission in a gymnasium are investigated. The investigation was made for the purpose of clarifying how the dynamic environment, such as air currents produced by an air-conditioning system, would influence sound propagation in a large indoor space.

The process of investigation was as follows.

Firstly, the statistical analysis was made to make the feature clear. The distribution of SPL changes was examined in order to derive the acoustical model with time varying system.

Secondly, SPL was simulated by above acoustical model which was derived from before examinations, and its distribution was also examined.

It was confirmed that there was a large fluctuation in SPL at high frequency ranges in a large indoor space. Based on statistical analysis of SPL fluctuation, a sound transmission model that incorporates a time variant system was proposed.

2.2 Sound pressure level measurement

2.2.1 Measurement condition

SPL was measured in a gymnasium because the gymnasium allowed for a large mean free path and its interior was made with hard materials which could lower the attenuation of reflected sounds (ℓ: 89.4 m, ω: 67.6 m, h: 18.0 m, 5,000 seats and reverberation time is 2.1 s at 500-Hz).

Table 1 shows the experimental conditions. The maximum air speed at the outlet duct was about 8 m/s. We could not measure the air speed and the direction throughout the room, but the air speed did not exceed 0.5 m/s in the audience area at 1.5 m above the floor level (Case 2). There are 36 outlet ducts with a diameter of 45 cm and 44 ducts with a diameter of 75 cm on the ceiling. Figure 1 shows the location of 11 observation points and sound source point. Figure 2 shows the location of outlet ducts on the ceiling. Figure 3 shows the structure of the outlet ducts. Airflow was divided by 3 direction by the nozzle structure. Figure 4 shows the image illustration of the air movement in this gymnasium. The vertical temperature difference from floor to ceiling did not exceed 3 ℃ in the condition of air conditioner on and off. Figure 5 shows the temperature gradients from floor to ceiling. Temperature was thought to be uniform in the horizontal way. A dodecahedron loudspeaker was used to produce pure tones of 0.5 and 1-kHz, and a plasma loudspeaker was used for 2-, 4-, 8- and 16-kHz frequencies. The height of the observation point was 1.5 m above the floor, and observation points were 1.2 m above the floor. The distance between the sound source and the observation points was about from 27 m to 57 m. SPL was recorded for about one minute at each observation point. Figure 6 shows a block diagram of the measurement.

Table. 1 The experimental conditions.

Case	Air conditioner	Air speed in audience area [m/s]	Noise criteria
1	off	≈ 0.0	NC - 25
2	on	< 0.5	NC - 40

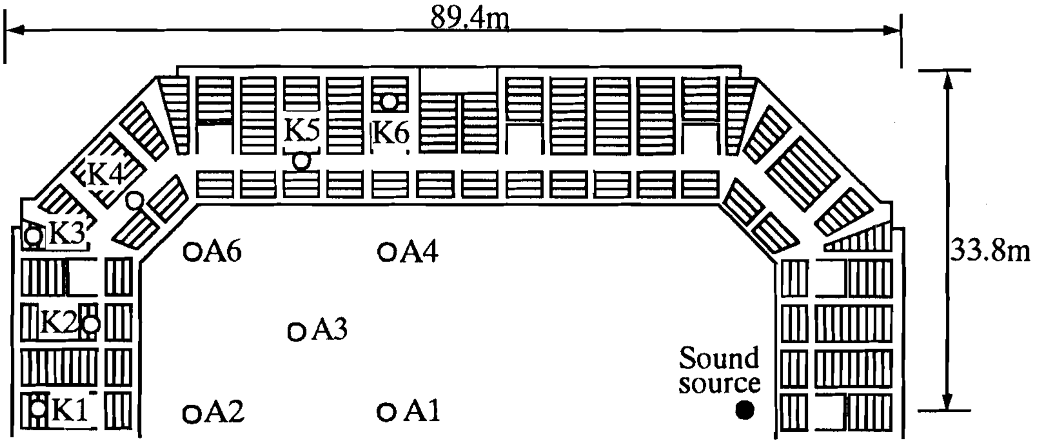


Fig. 1 Location of observation points. (● : sound source, ○ : observation points, A1 – A5 were set on the floor, K1 – K6 were set around the audience stand.)

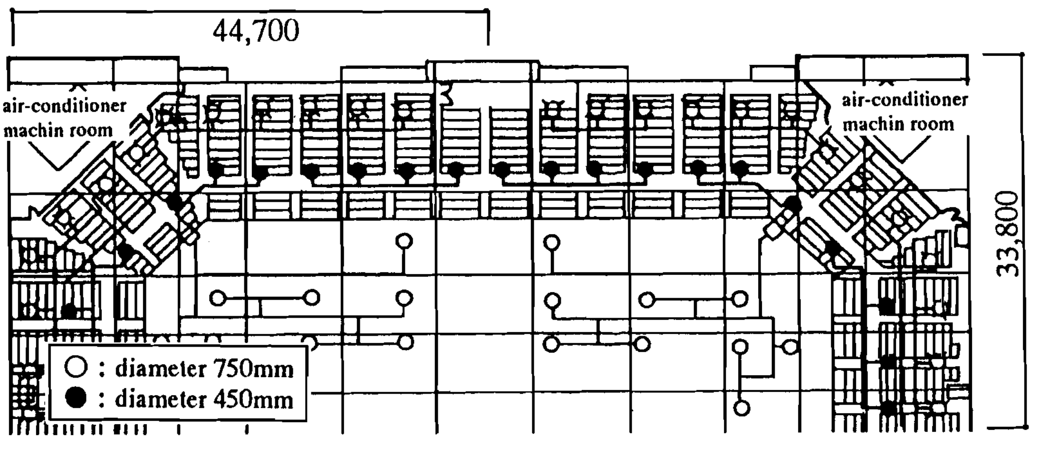


Fig. 2 Location of outlet ducts on the ceiling.

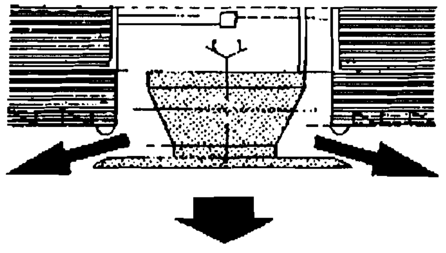


Fig. 3 The structure of outlet ducts. Air-flow was divided into two directions, that are vertical and diagonal.

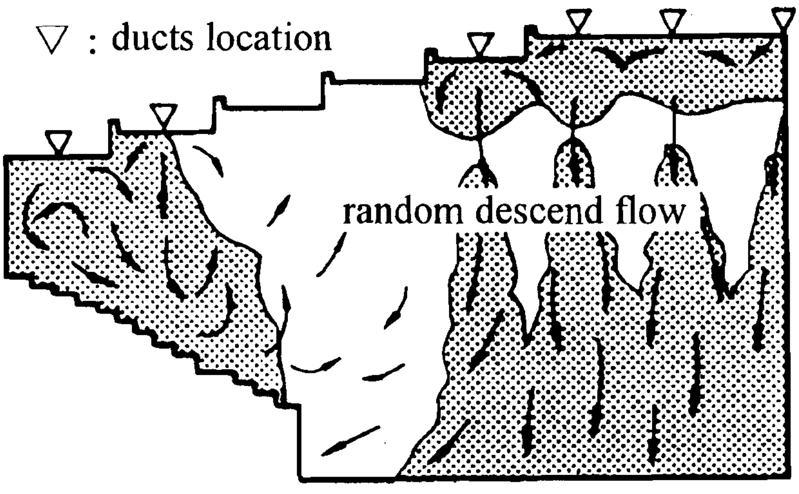


Fig. 4 The image illustration of airflow movement in gymnasium. (The vertical section).

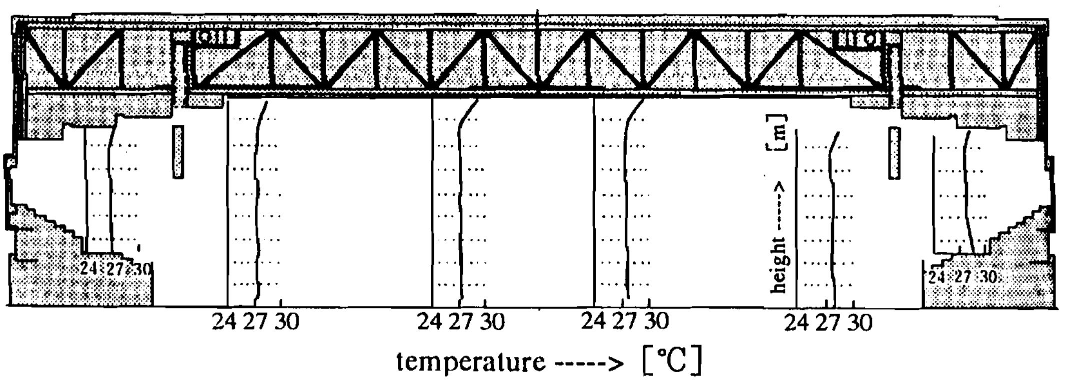


Fig. 5 Temperature gradients from floor level to ceiling.

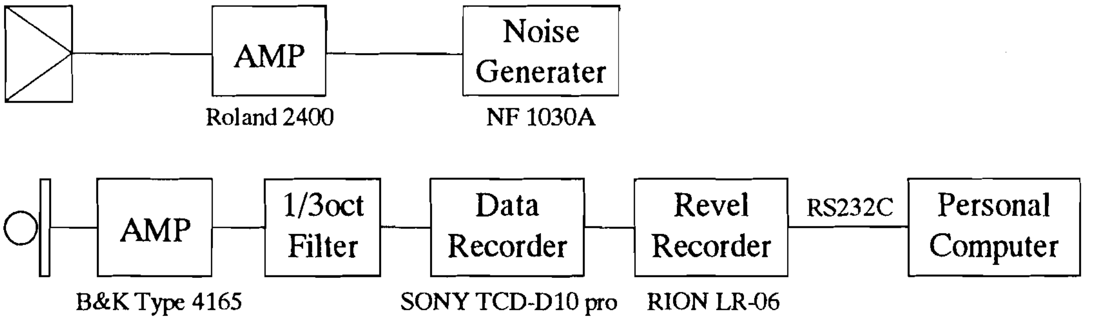


Fig. 6 A block diagram of experimental set-up.

2.3 Results of measurement

2.3.1 Fluctuation of SPL

Figure 7 and 8 shows the SPL fluctuation recorded at observation point A1 and K1 (from 0.5 kHz to 16.0 kHz). Figure 9 and Table 2 shows the mean standard deviation of SPL change and standard deviations which was measured at 11 observation points.

In Case 1, the strong SPL change was not observed at any frequencies or observation points. In Case 2, the strong SPL fluctuations were clearly observed at frequencies higher than 2.0-kHz. As the frequency increased, SPL fluctuation became stronger. These tendencies were apparent regardless of the distance between the sound source and the observation point.

At several observation points, the existence of SPL fluctuation at 0.5-kHz could be detected. From the study of the discrimination of SPL change ($\varDelta_{spl}$), it was reported that the $\varDelta_{spl}$ was 0.7 dB, in the case of 1.0-kHz sine wave as sound stimulus.

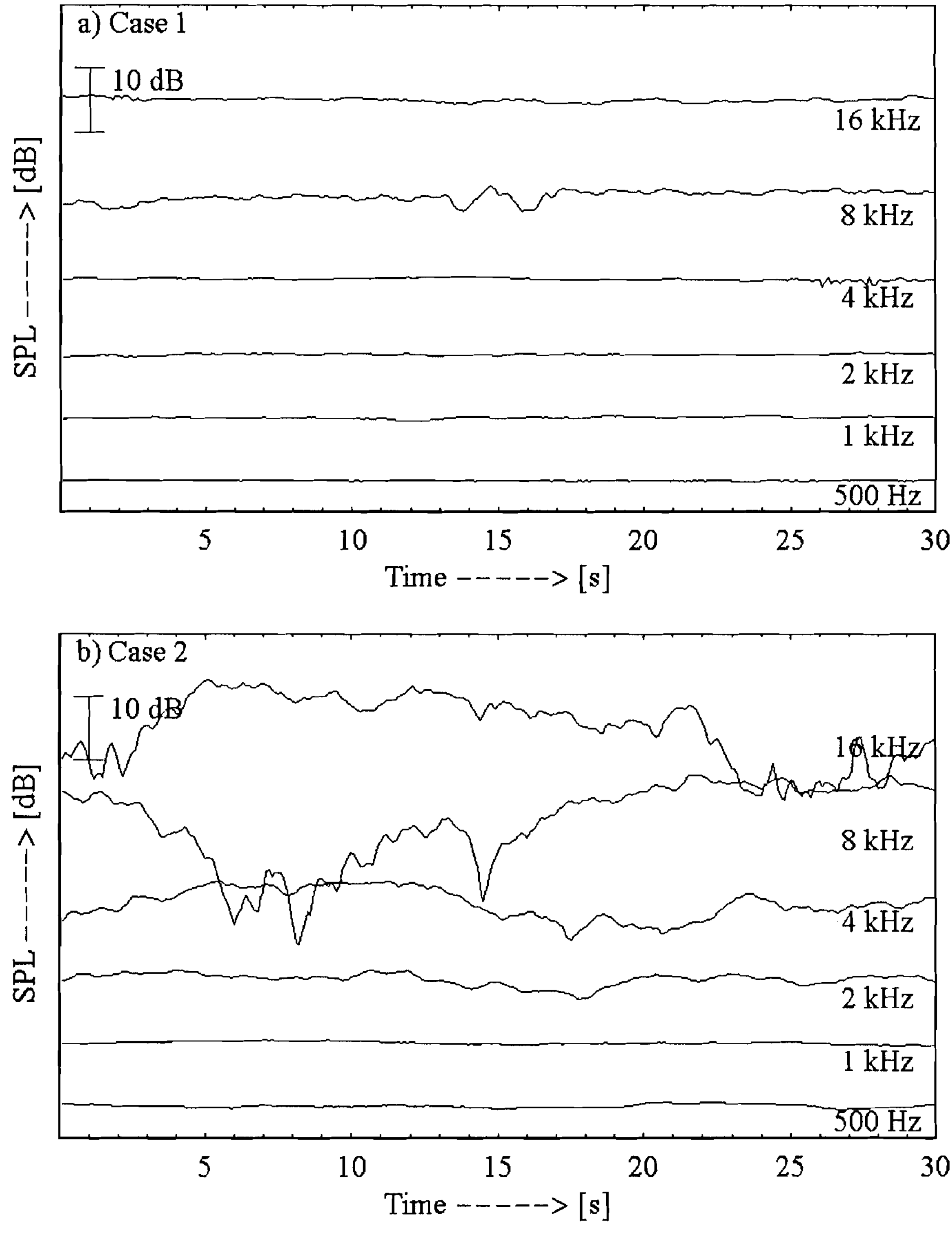


Fig. 7 The SPL fluctuation recorded at observation point, A1.
(Upper : Case 1, Lower : Case 2)

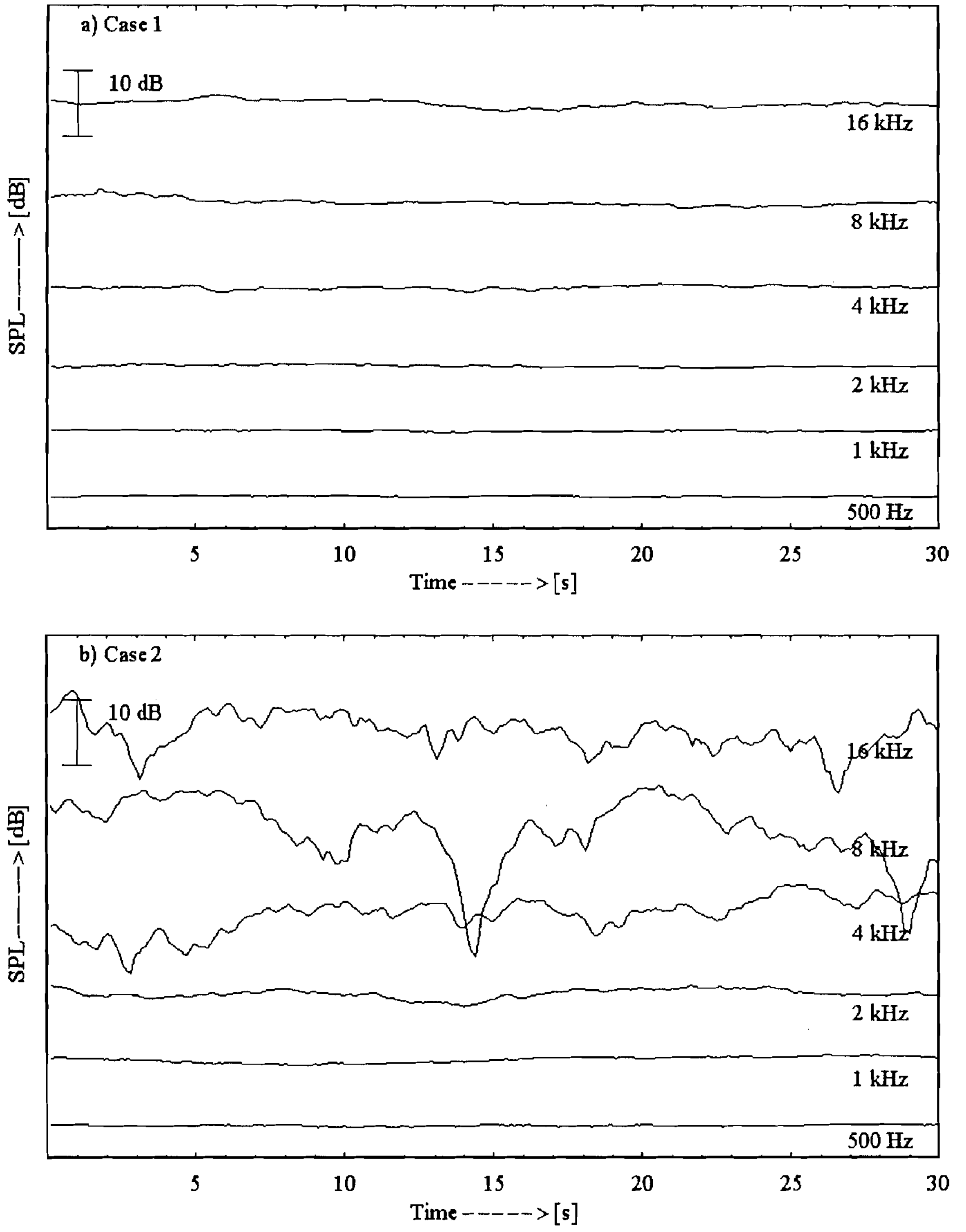


Fig. 8 The SPL fluctuation at observation point, K1.
(Upper : Case 1, Lower : Case 2)

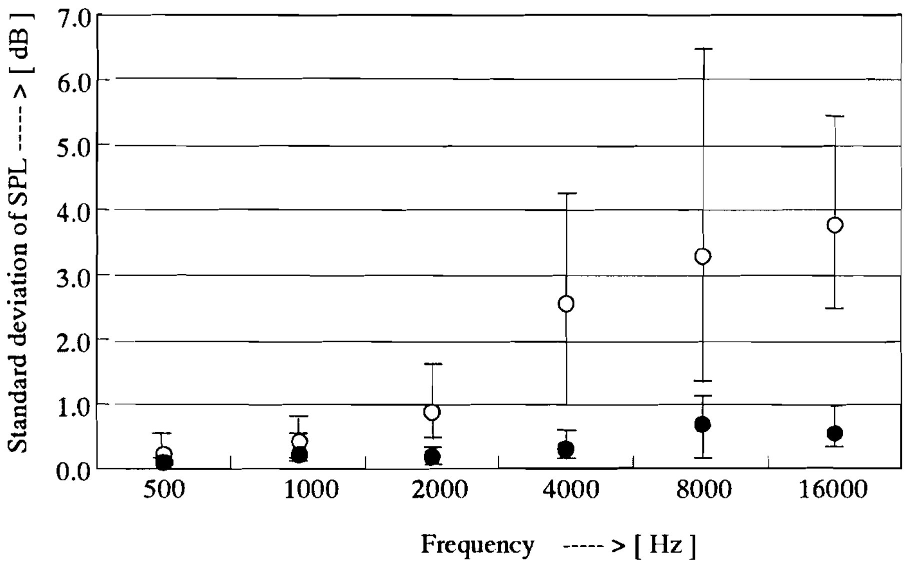


Fig. 9 Mean standard deviation of SPL change at 11 observation points. (● shows the mean standard deviations of 11 points in Case 1 and ○ in Case 2. Top and bottom bars show the maximum and minimum standard deviation of SPL.)

Table. 2 Mean standard deviation of SPL change of 11 observation points .

(unit : dB)

		0.5-kHz	1.0-kHz	2.0-kHz	4.0-kHz	8.0-kHz	16.0-kHz
Case 1	Mean value of SD	0.21	0.19	0.20	0.43	0.97	0.58
Case 2	Mean value of SD	0.31	0.57	0.87	2.53	3.29	3.76

2.3.2 Statistical analysis of amplitude change

In this section, statistical analysis was performed in order to make the feature of SPL fluctuation clear, and to search the mechanism.

When waves of differing amplitude and phase are synthesized irregularly, they can be characterized by Rayleigh or Nakagami-Rice distribution. The measured amplitude was compared with Gamma distribution, which includes Rayleigh, Gauss and approximately Nakagami-Rice distributions, to evaluate how reflected sounds are composed. Table 3 shows the classification in terms of statistical character of amplitude change. These statistical characteristics of amplitude change are shown in Appendix A.

The general formula of this distribution is

$$p(x;P^2) = \frac{1}{m^{l+1}\Gamma(l+1)} x^l e^{-x^2/m}, \qquad (1)$$

Where $\overline{P^2}(=m(l+1))$ is the mean value, and $\sigma(=m\sqrt{l+1})$ is the standard deviation. The parameter l represents the degree of fluctuation. In the case of when l equals 1.0, the distribution is equivalent to Rayleigh distribution, and when l >1.0, it is approximately equal to Nakagami-Rice distribution. Parameter l and m were chosen as follows. The simple correlation coefficient between the distribution of measured data and theory were calculated. When the value of this simple coefficient was more than 0.98, we chose the values of l and m by changing the parameter l gradually such that $l = 0, 1, 2, \cdots$.

Figure 11 and 12 shows an example of the cumulative density of the measured values compared with Gamma distribution. Figure 10 shows the mean values of parameter l representing the degree of modulation at each point.

In both cases, the measured values agreed with this theoretical curve. The slope of the cumulative density curve for Case 1 is steeper than that for Case 2. Because l is more than 0.0, SPL fluctuation must be caused by the composition of a regular wave with irregular waves. As the frequency becomes higher, the value of l

of l becomes smaller. It is considered that the ratio of irregular components to the regular components differed in each case.

Table. 3 The relationship between statistical characteristics and the condition of wave composition.

Wave composition	Distribution of amplitude	Distribution of mean-squared amplitude
a) Differing amplitude and phase waves synthesized	Rayleigh distribution	Gamma distribution ($l = 0.0$)
b) Steady waves synthesized with above irregular waves	Nakagami-Rician distribution	Gamma distribution ($l > 0.0$)

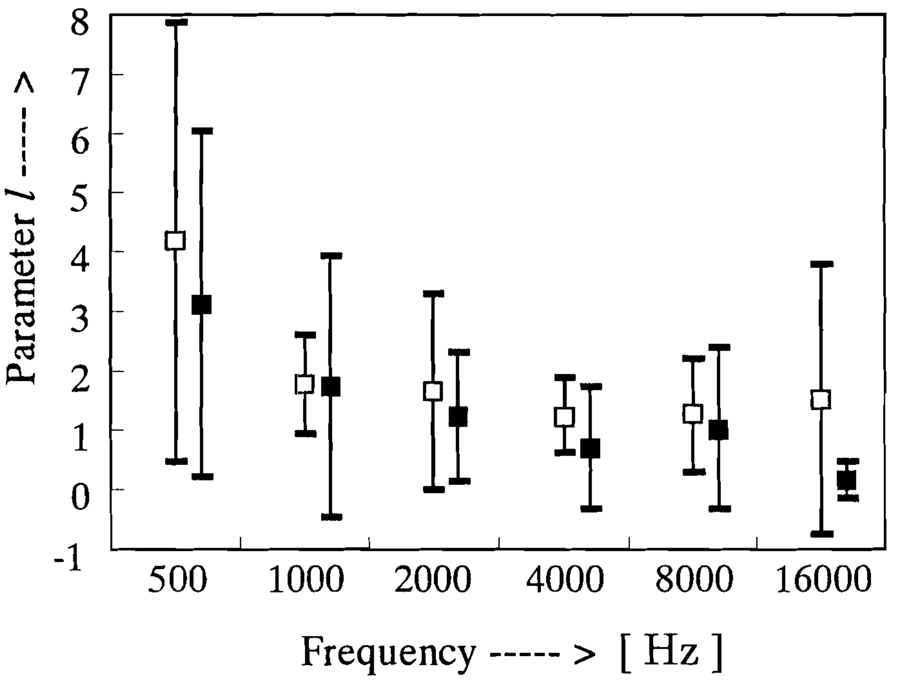


Fig. 10 The mean value of parameter l at each frequency.(□ is the mean value of l in Case 1 and ■ is in Case 2. The top and bottom bars show ± 1 SD.)

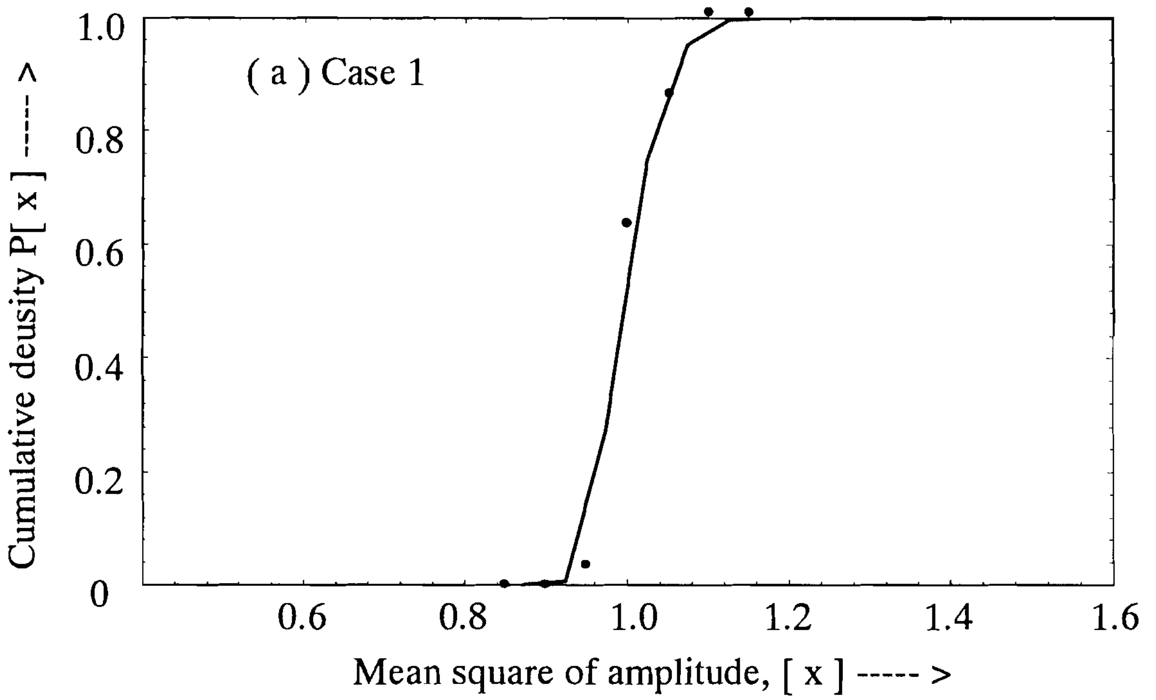


Fig. 11 The cumulative density of the mean-squared amplitude. (Observation point : K1, Frequency : 2.0-kHz)

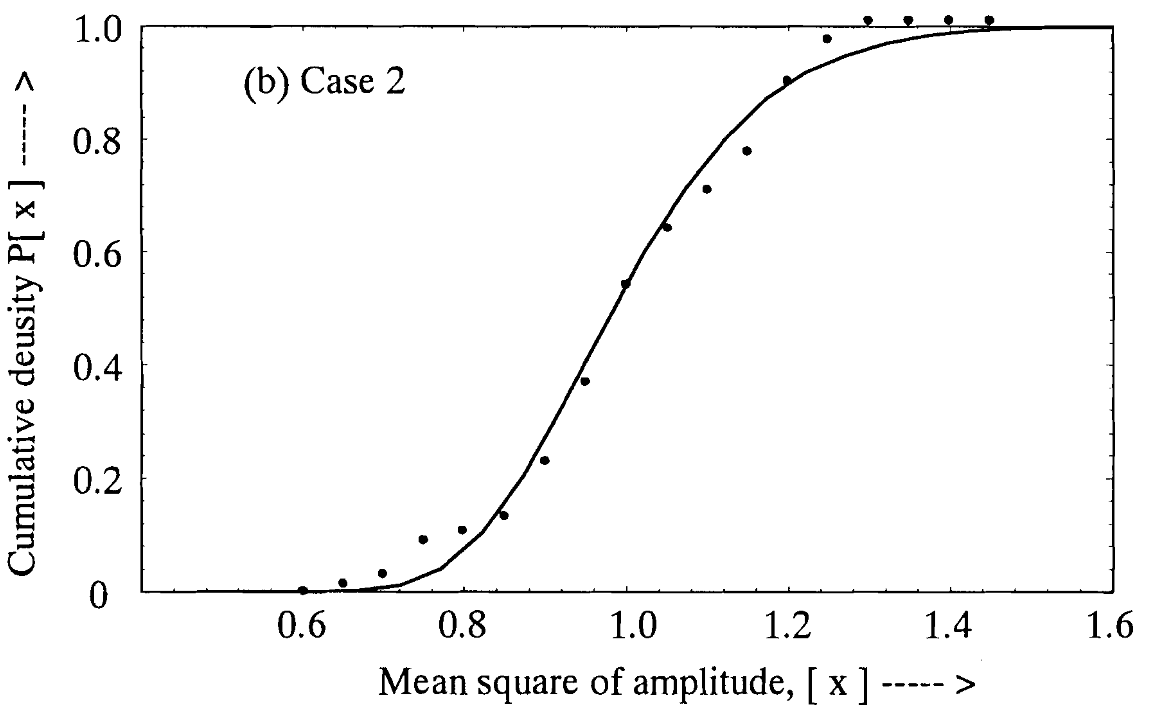


Fig. 12 The cumulative density of the mean-squared pressure. (Observation point : K1, Frequency : 2.0-kHz)

2.4 Time variant model of impulse response

2.4.1 Concept of the acoustical model

The sound pressure at the observation point is usually represented by

$$p(t) = \sum_{n=0}^{\infty} f(t) * R_n h_n (t - t_n), \qquad (2)$$

where R_n is the amplitude of each reflection ($n = 0$ represents the direct sound), t_n is the delay time of each reflection, and $f(t)$ shows the signal of sound source. It is supposed that following formula (3) of a time-variant impulse response model in which the delay time of reflection varies in time represents the mechanism of SPL change.

$$p(t) = \sum_{n=0}^{\infty} f(t) * R_n h_n (t - t_n(t)), \qquad (3)$$

Where, $t_n(t)$ is defined by α_n and $\beta_n(t)$. In order to represent the delay time with modulation, equation (4) can be introduced as follows.

$$t_n(t) = t_{n0} + \alpha_n t_{n0} \beta(t) = t_{n0}(1 + \alpha_n \beta_n(t)), \qquad (4)$$

where α_n is the modulation interval of delay time, $\beta_n(t)$ is change of the property of delay time, t_{n0} is the initial value for delay time under the geometry ray theory, and $< t_n(t) > = t_{n0}$. By substituting the above equation (4) into formula (2), expression (5) can be derived.

$$p(t) = \sum_{n=0}^{\infty} f(t) * R_n h_n (t - t_{n0}(1 + \alpha_n \beta_n(t))), \qquad (5)$$

It is simply supposed that α_n becomes larger as delay time increases. Figure 13 shows the concept of this impulse response including a time variant system.

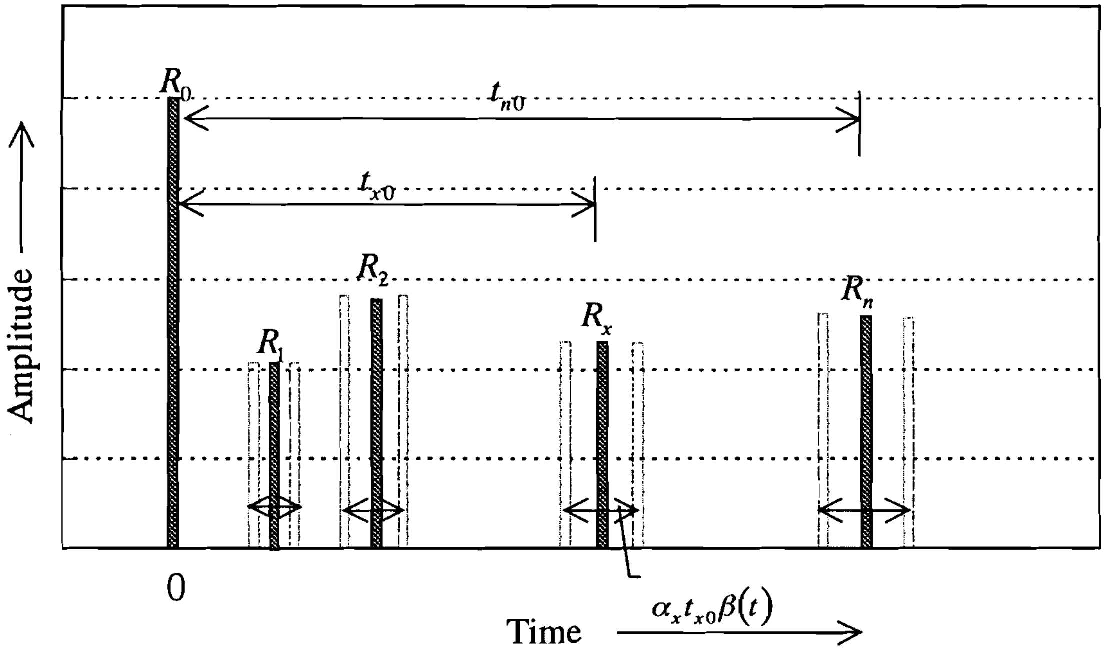


Fig. 13 An impulse response including a time variant system. (The dark lines showing the initial delay time of reflections. The arrow width shows the modulation interval of each reflection.)

2.4.2 Statistical characteristics of the acoustical model

The statistical character of mean-squared amplitude for the model was examined as follows.
In this time, $f(t)$ is equivalent to a sine wave, the sound pressure at a point can be represented as follows,

$$p(t) = \sum_n \sin\omega t * R_n h_n(t - t_n)$$

$$= \sum_n R_n \sin(\omega t - \omega t_n)$$

$$= \{R_0 \sin\omega t_0 + R_1 \sin(\omega t - \omega t_1) + R_2 \sin(\omega t - \omega t_2) + \cdots\}, \qquad (6)$$

$$= \sin\omega t(R_0 + R_1 \cos\omega t_1 + R_2 \cos\omega t_2 + \cdots)$$

$$+ \cos\omega t(R_1 \sin\omega t_1 + R_2 \sin\omega t_2 + \cdots)$$

When t_n distributes according to formula (4), ωt_n are simply denoted by a_n .

$$p(t) = \sin\omega t(R_0 + R_1 \sum_i^{n1} \cos a_i + R_2 \sum_j^{n2} \cos a_j + \cdots)$$

$$+ \cos\omega t(R_1 \sum_i^{n1} \sin a_i + R_2 \sum_j^{n2} \sin a_j + \cdots), \qquad (7)$$

$$= \sin\omega t(R_0 + r_1 + r_2 + \cdots) + \cos\omega t(s_1 + s_2 + \cdots)$$

$$= \sin\omega t(R_0 + r) + \cos\omega t(s)$$

The distribution of a_i is flat ($0 \leqq a_i \leqq 2\pi$). However, it approaches normality as $n1, n2, \cdots \rightarrow \infty$, due to the central limit theorem. Consequently the distribution of each term including the trigonometric function becomes a normal distribution. The variables r_1, r_2, s_1, s_2, etc, are normally distributed variables. Since the normal distribution reproduces itself by composition, r and s are also normal variables. The fundamental equation of Nakagami-Rice distribution is

$$\overline{p^2} = \frac{1}{2}\left[(R_0 + r)^2 + s^2\right] \tag{8}$$

Consequently, the distribution of this model can be approximately applied to Gamma distribution.

2.5 SPL simulation

2.5.1 Condition of SPL simulation

In this section, SPL simulation was made to examine the reality sound field. SPL was simulated in order to confirm the appropriateness of this time-variant model for the measured SPL change. The initial values for delay time t_{n0} and amplitude R_n of each reflected sound were calculated at each observation point in the gymnasium using the geometrical sound ray theory. The conditions of this calculation are as follows.

The delay time of reflections was within 500 ms from the direct sound, and the reflection frequency was within 3 times. The sound source and receiving points were set at the same points that the measurement was done. Figure 14 shows the gymnasium model basing on the geometrical theory. Figure 15 shows the impulse response calculated by this model.

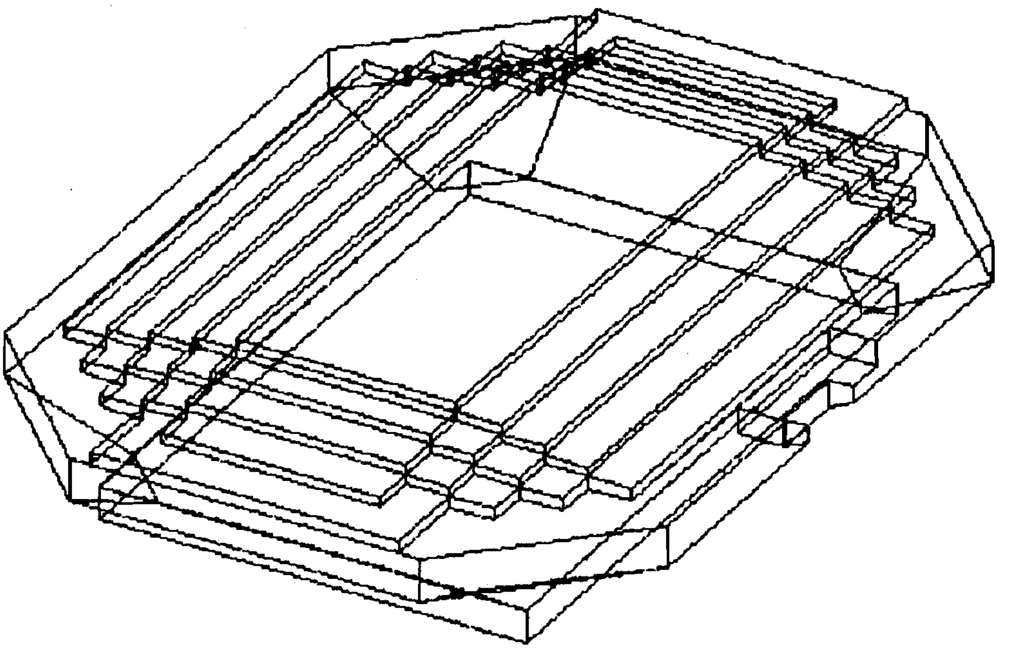
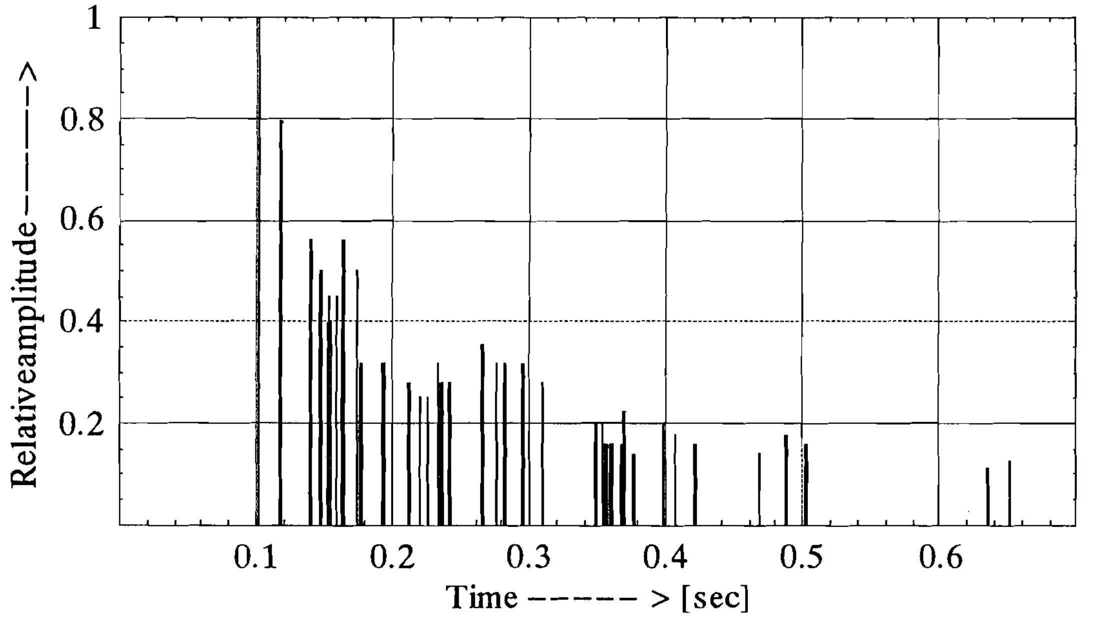


Fig. 14 The geometrical model of this gymnasium. (Floor: wood flooring, Wall: concrete, Ceiling: rock wool board.)



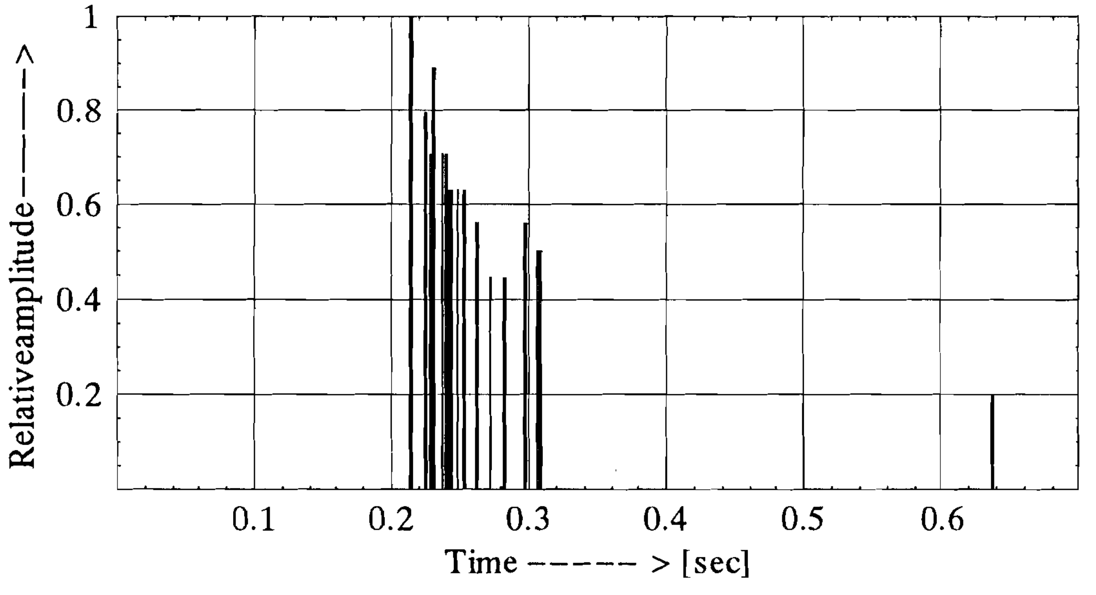


Fig. 15 Examples of impulse response, which are calculated by the model in, figure 13 on the basis of geometry sound theory. (Upper: observation point, A1, Lower: K2)

2.5.2 Examination of modulation pattern, $\beta(t)$

Before performing the SPL simulation, the modulation pattern of delay time ($\beta(t)$) was examined.

The modulation pattern of delay time ($\beta(t)$) can be adopted by random noise, periodical waves (like sine waves), and band waves. It can be considered that SPL calculated by random noise would change randomly, and that by periodical waves would change periodically. SPL simulations were made by using each modulation pattern of delay time for reflections, 0.1-Hz Oct-band wave, 1.0-Hz Oct-band wave, 1.0-Hz sin wave and white noise. Figure 16 shows the results calculated SPL by each modulation pattern, and were compared to measured date. Figure 17 shows the envelope frequency of SPL change. It was supposed that the frequency character of SPL relates the modulation pattern.

And there are also many other types of modulation patterns in octave band waves, so 1/1 octave band noise was chosen and examined. The fluctuation interval (α_n) is controlled so that it has the same standard deviation as that of the measured data. Figure 18 shows the measured SPL and the calculated SPL modulated by octave-band waves from 0.1-to 0.5-Hz (at observation point K1, 2.0 kHz). The higher frequency of the modulation becomes, the more the simulated SPL is fluctuated. Next the frequency envelope of SPL change is to be examined (Figure 19). The frequency envelope of simulated SPL change by 0.2-Hz octave-band wave resembles that of measured data at this point. Figure 20 shows the SPL from 0.5- to 16.0-KHz, calculated by 0.2-Hz octave-band wave. The characteristic of SPL change is similar to that of measured data.

In previous study concerning the detection of fluctuation, the normal rate of fluctuation in good vibrato was between six and seven per second, i.e. 0.14~0.17 Hz (Carl Seashore, 1936).

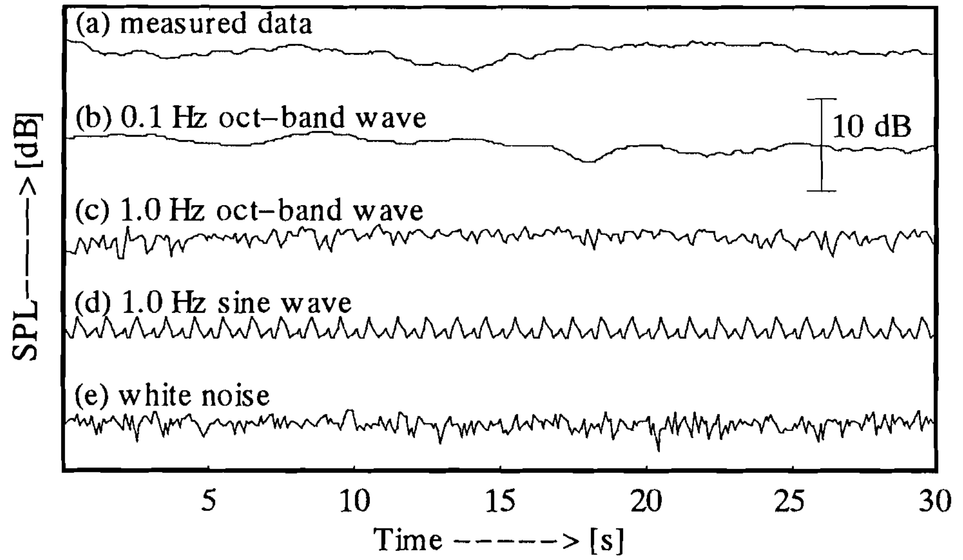


Fig. 16 The comparison of SPL simulated by each modulation pattern of delay time. (K1, 2.0-kHz, (a) measured data, (b) 0.1-Hz octave-band, (c) 1.0-Hz octave-band, (d) 1.0-Hz sine wave, (e) white noise).

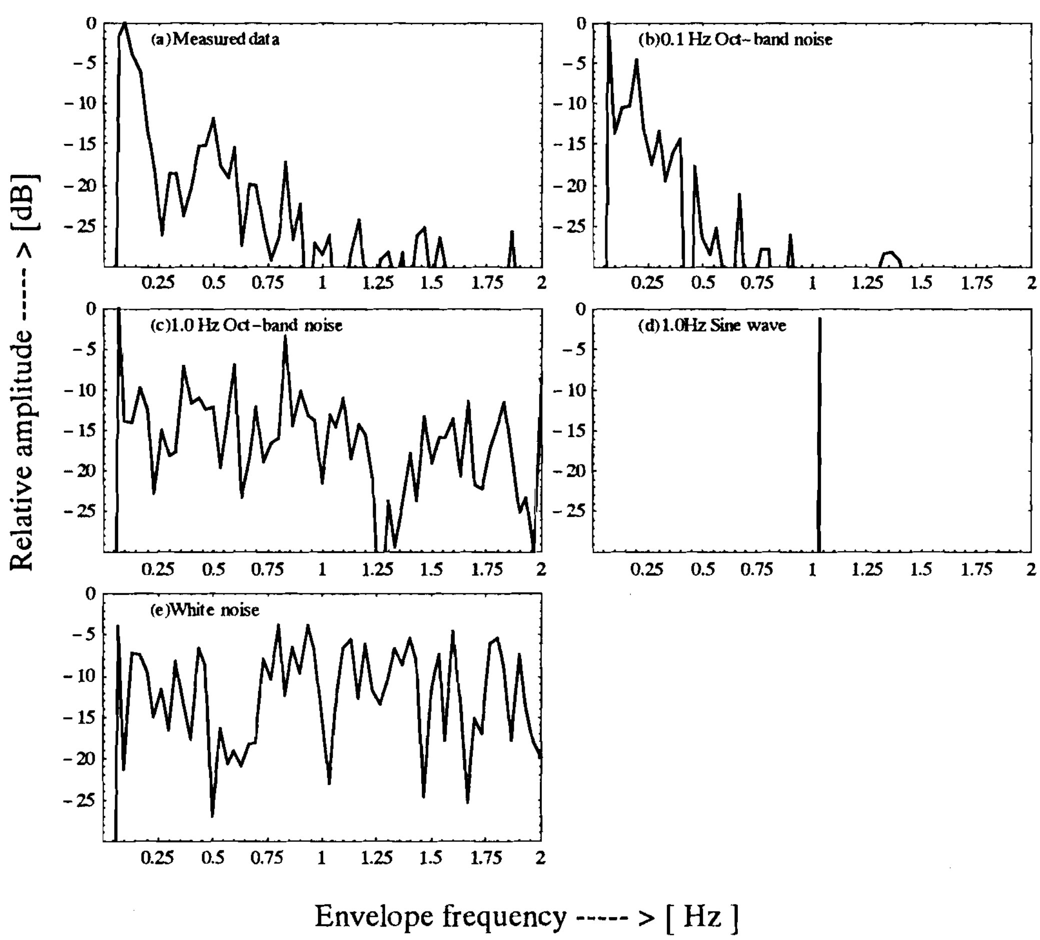


Fig. 17 Envelope frequency by each modulation pattern of simulated SPL. (Observation point K1)

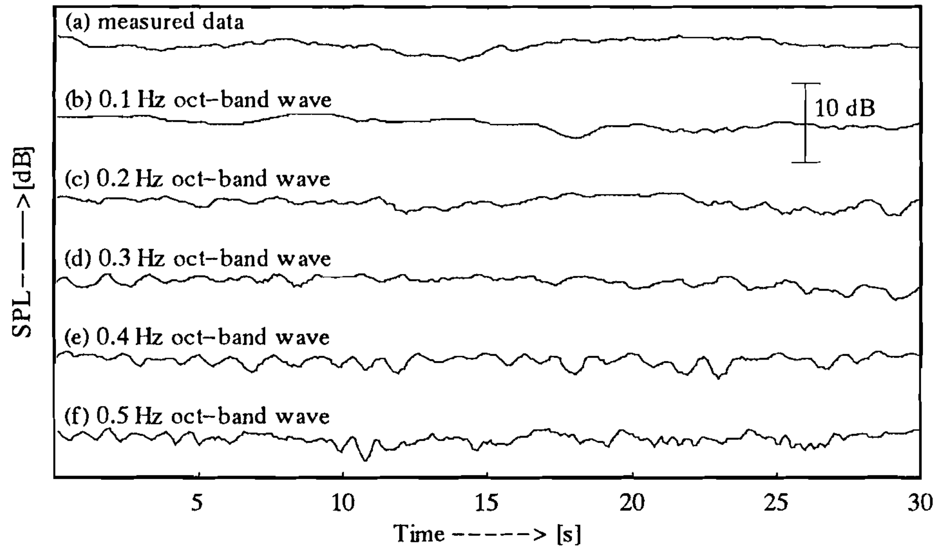


Fig. 18 The comparison of SPL simulated by each modulation pattern of delay time. (K1, 2.0-kHz, (a) measured data, (b) 0.1-Hz Oct-band, (c) 0.2-Hz Oct-band, (d) 0.3-Hz Oct-band, (e) 0.4-Hz Oct-band, (f) 0.5-Hz Oct-band).

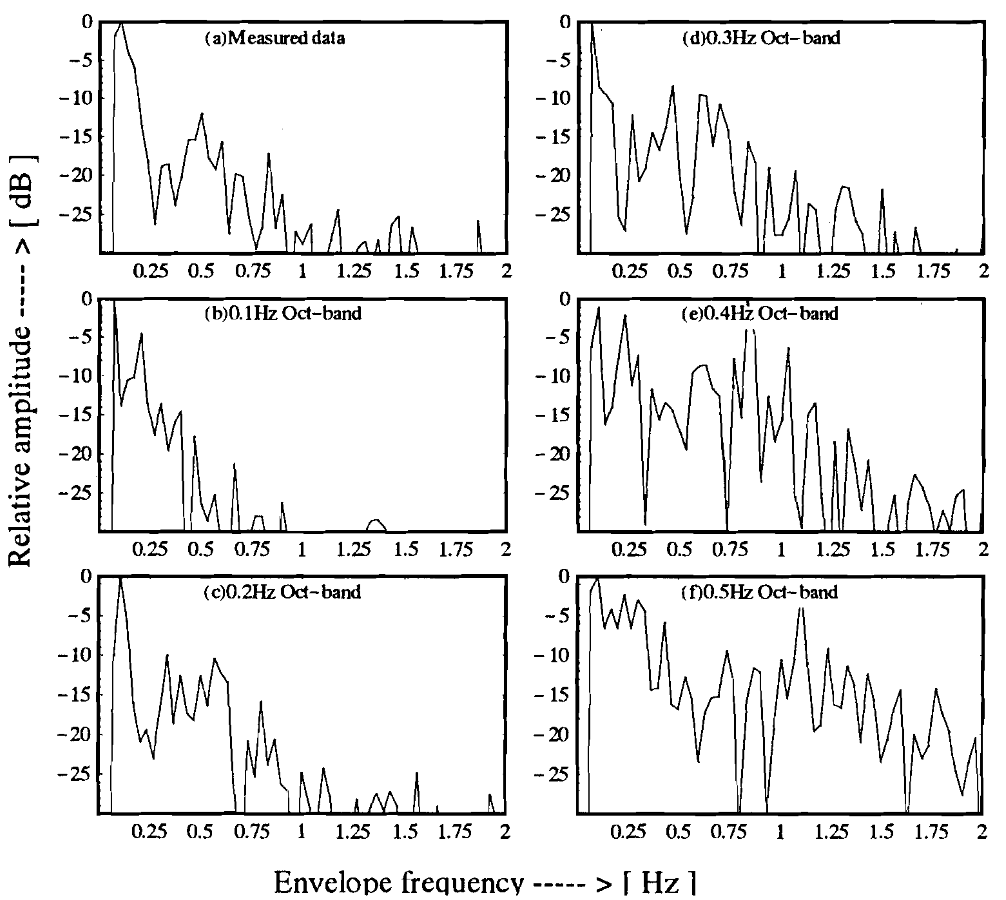


Fig. 19 Envelope frequency of simulated SPL by each modulation pattern. (Observation point K1)

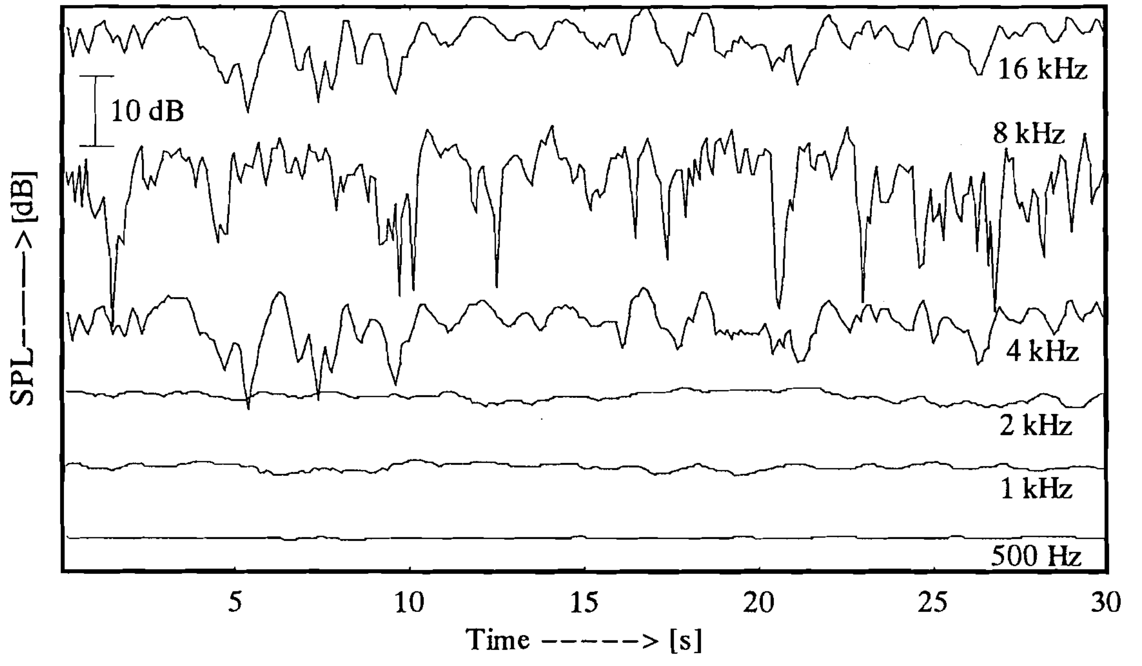


Fig. 20 The calculated SPL by using 0.2-Hz Oct-band noise at receiving point K1. (Showing the frequencies of sine wave from 0.5- kHz to 16.0- kHz.)

2.5.3 Statistical distribution of simulated amplitude

The cumulative density of the mean-squared amplitude at 2 kHz of Figure 20 is also compared with Gamma distribution of Figure 12. The cumulative density of the amplitude fits Gamma distribution well, as does the measured data.

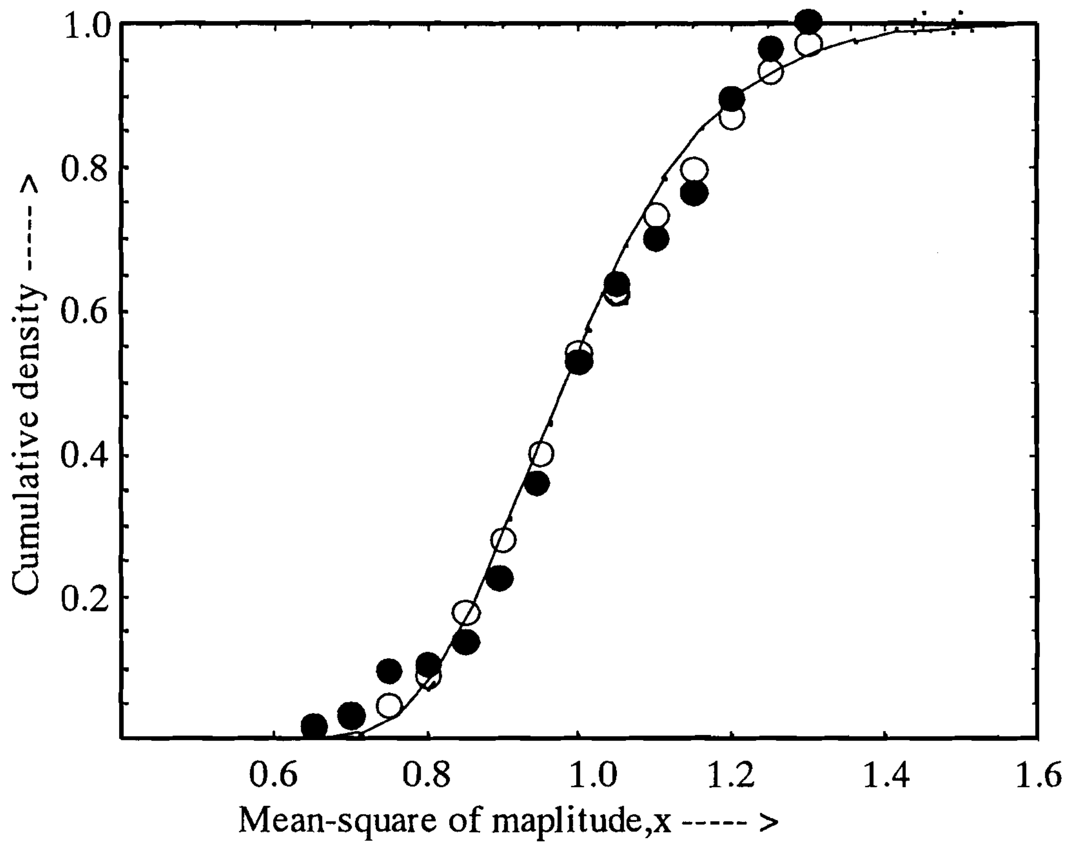


Fig. 21 The cumulative density between the measured and calculated mean-squared amplitude with the gamma distribution. (K1, 2.0-kHz, ○: the calculated mean-squared pressure, ●: the measured mean-squared pressure. The solid line indicates the gamma distribution)

2.6 Conclusions

From the analyses of SPL change and the statistical distribution of amplitude change for both measurement conditions (air conditioning on and off) the following conclusions, can be inducted.

A change in SPL is observed when the air conditioning is on. The influence is significant in the frequency domain, above 2.0-kHz. The higher frequency becomes, more SPL fluctuates. Since the distribution of amplitude agrees with Gamma distribution, SPL change occurs resulting from the combination of the direct wave (regular) and the changing delay time of reflected sounds (irregular).

A time-variant impulse response in which the delay time of reflected sound changes over time is devised. Based on the comparison of the simulated SPL, using some modulation pattern of delay time with the measured SPL, it is found that SPL fluctuation becomes stronger as the modulation frequency became higher. From the analysis of envelope frequency in SPL change, the envelope of the measured data resembles that of the 0.2-Hz Oct-band wave. SPL calculated by using 0.2-Hz Oct-band noise shows the same characteristics as the measured data, and the cumulative density of the mean-squared pressure corresponds to Gamma distribution.

It may not be so hard to confirm the appropriateness of time variant model in this case. The air current was thought to be the factor that led the SPL change in this chapter. However there are some other factors relating to the fluctuation of SPL, such as the air speed at outlet ducts, the system of air conditioning, temperature gradients and the movement of a player and an audience. The effects and its extent must be examined furthermore.

The impulse response including time variant system would be used at the stage of the psychological experiments in Chapter III and IV.

CHAPTER Ⅲ

EFFECTS OF TIME VARIANT SOUND FIELD ON SUBJECTIVE JUDGMENT (JND)

3.1 Preface

Chapter Ⅲ and Ⅳ descrived the effects of fluctuations on subjective judgment (psychological aspect) obtained from the results of three psychological experiments. First experiment is concerning with the differential threshold (just noticeable difference) of fluctuation, and its results is showed in Chapter Ⅲ. Second and third experiment were concerned with subjective preference, and their results is showed in Chapter Ⅳ.

Concerning the subjective judgment of the sound field, psychological tests related to perception of colouration were performed[4] in the past time. The result of this experiment suggested the effectiveness of the auto-correlation function (ACF) with regard to the sense of hearing in the temporal domain.

This first experiment was performed with respect to the effect on subjective judgment of sound field variation to identify the psychological standards for subjective preference. An acoustic model of the impulse response taking account of variations of medium was used as sound stimuli. For the subjective evaluation of sound field variation, the subject was asked to judge just noticeable difference (JND) in colouration. Also, the relation between the ACF of sound stimulus and JND was investigated.

From the results of this experiment, modulation interval (Δ) at JND of colouration increased, as the modulation frequency decreased. In the case of Motif A, a low tempo sound source, JND of Δ was smaller than Motif B, a fast tempo sound source.

3.2 Colouration

Just noticeable difference of colouration was selected as a parameter of subjective judgment.

It was found that the superposition of a strong isolated reflection (whose delay time was within several milli-seconds) to the direct sound could cause another undesirable effect, in particular with music, called 'colouration', i.e. a characteristic change of the signal spectrum. The same is true for a regular, i.e. equidistant succession of reflection (Kutruff "ROOM ACOUSTICS"). Figure 22 shows the example of the Fourier transform of impulse response. So the definition of the colour of a sound is given here in analogy with definitions of pitch and timbre as is found in the American Standard of Acoustical Terminology (A.S.A.T). However A.S.A.T dose not have a definition of 'colour' or 'colouration', therefore a definition was proposed in analogy with the above expressions. An example of definitions of colour or colouration of a sound signal could be given as follows: "the colour of a sound signal is that attribute of cochlear sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness are dissimilar". It means that colouration can be perceived easily when the coloured signal is compared to the original signal. This is not always available, and therefore it is often said that colouration is judged by comparing a signal to an 'internal reference'. Colouration is regarded as one of the sound obstacles. So it is thought that this colouration should be removed in the case of sound designing for concert hall and recording sound field.

Whereas time structure of sound stimulus was consisted of the direct sound and modulated delay time of the first reflection in order to simulate the fluctuation in acoustical transform function in this experiment. Delays time interval of reflection that was several milli-seconds in this experiment also leads colouration of sound stimulus.

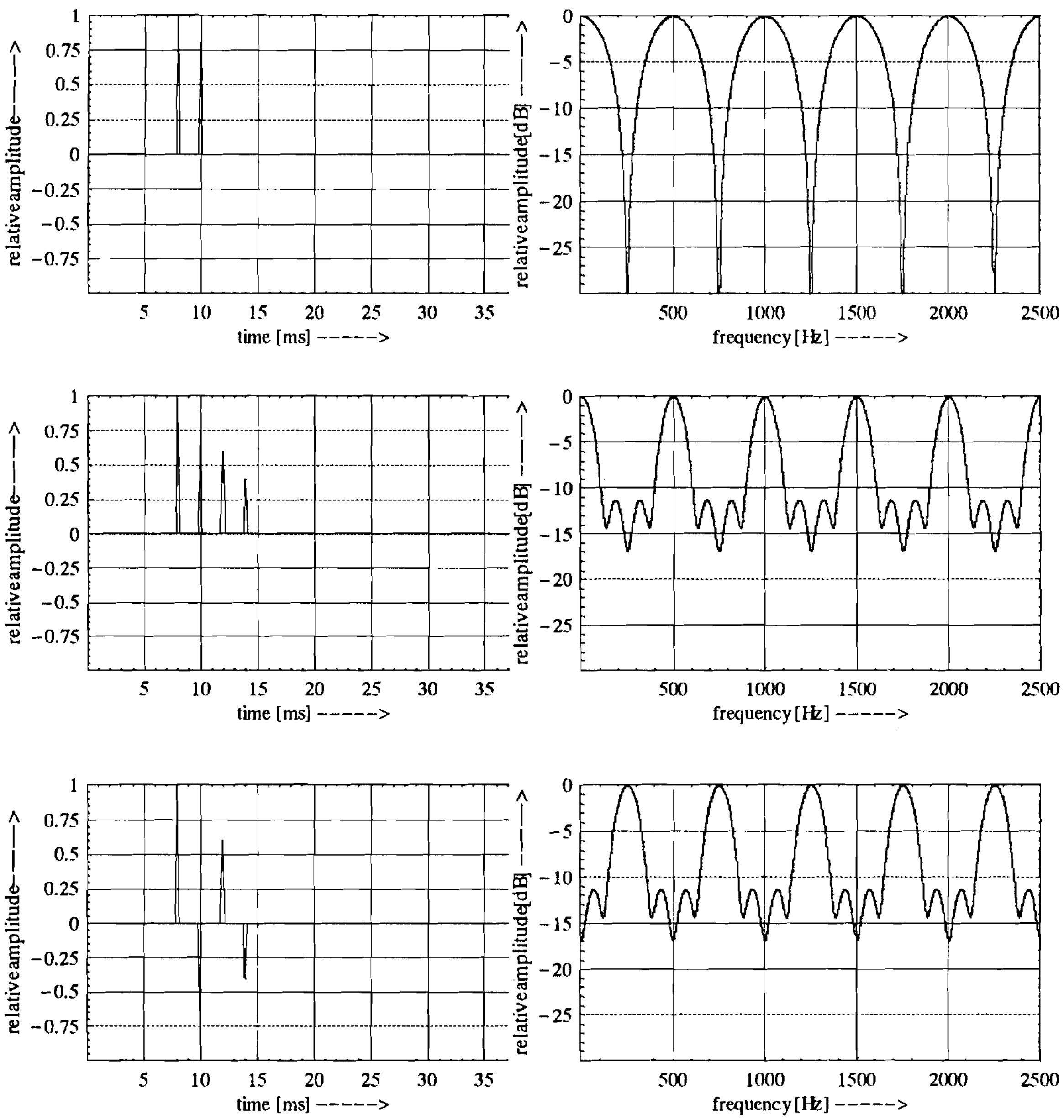


Fig.22 Impluse responses (left side) and absolute values of transmission functions of various comb filters (right side). When the interval of the delay time is t_0, the interval of frequency peak would be $1/t_0$. Upper case, t_0 = 2.5 ms, $1/t_0$ = 500 Hz.

3.3 Experiment condition

In preliminary experiments, pure tones, noise bands, and chords were used as the sound source, but it was found that the sound pressure level varied considerably as a result of the relation between the direct sound and reflected sound. Therefore it was decided to use musical sound as the sound source for the experiments. In order to observe the effects of the effective duration of the ACF (τ_e), musical sounds of differing tempos, as shown in Table 4, recorded in an anechoic room, were chosen.

Figure 23 shows the definition of the time structure for the stimulus and the fluctuation span of Δt_1 (Δ). Using sound field of only the direct sound and the first reflection, the relative amplitude was made the same. Table 5 shows the conditions of the experiment. The initial value of Δt_1 was decided with regard to the preferred delay time of reflection obtained in psychological tests for each motif. The modulation frequency (Mf) of Δt_1 was controlled simply by a pure tone using a low frequency oscillator (LFO). As the Mf was considered to be below 1.0-Hz, four standards were chosen around 1.0-Hz. As the value of Δt_1 was decided according to the music, the standards were different. The continuation time of the sound stimulus was set at about 8 seconds, and the stimulus was presented paired with the sound stimulus without modulation being applied. The subject judged the JND of the colouration variation with adjustment in Δ. The judgment was carried out with respect to a maximum of 10 times repetitive presentation of the sound stimulus. The subjects were 5 male students between the ages of 22 and 24 years of age. Figure 24 shows a block diagram of the experimental set-up. The delay machine used was a DPS-M7 (Sony), and the loudspeaker was Bose Model 121.

Table. 4 Sound Source and τ_e of sound source.

Sound source	Title	Composer	τ_e [ms]
Motif A	Royal Pavane	Gibbons	127
Motif B	Sinfonietta	Malcolm Arnold	43

Table. 5 Test Conditions.

Sound source	Modulation frequency of Δt_1	Initial value of $[\Delta t_1]_p$
Motif A	0.2-, 0.4-, 0.8- and 1.6- [Hz]	120 [ms]
Motif B	0.4-, 0.8-, 1.6- and 3.2- [Hz]	40 [ms]

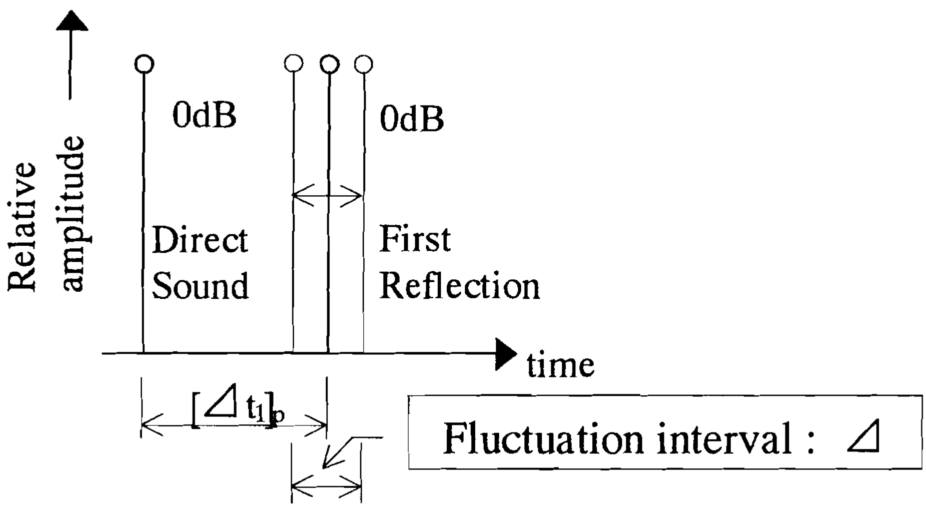


Fig. 23 Time structure of the direct sound and a variable reflection

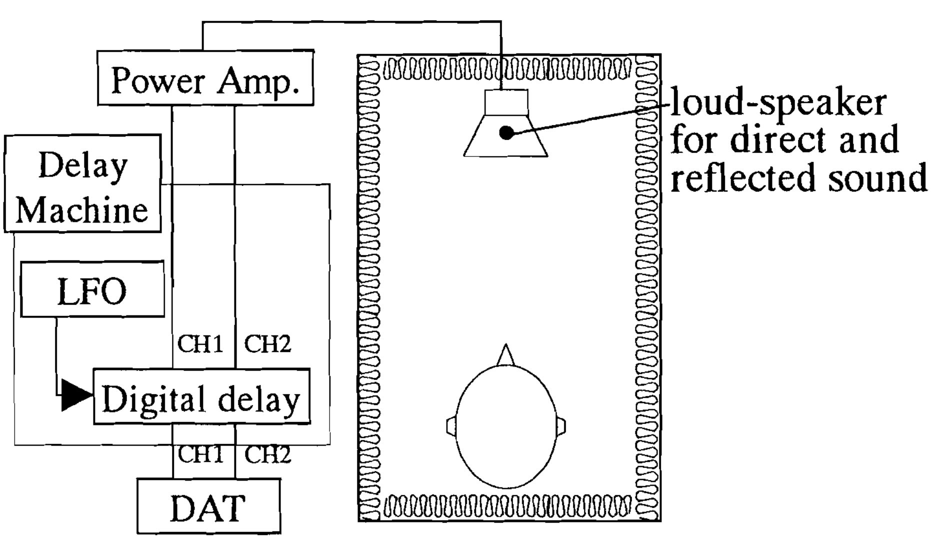


Fig. 24 Block diagram of experimented set-up.

3.4 Results and discussions

Figure 25 shows the relationship between Mf and averaged Δ at JND, as well as the standard deviation and the regression curves. From the figure it can be seen that for both Motif A and Motif B, as Mf becomes lower, Δ at JND increases and the standard deviations of Δ increase. The discernment of variation in colouration becomes difficult.

It was also observed that Δ at JND for Motif A, which has a long τ_e, were smaller and easier to discern than that for Motif B. From the test of significant difference with regard to Δ at each standard Mf (0.4-, 0.8-, and 1.6- Hz), it was found that there was a significant difference between Motif A and Motif B ($p<0.01$).

As shown below, the regression equations could be expressed in following forms and it can be seen that Motif A is related to Motif B by a simple translation.

$$\Delta(JND) \approx \frac{3.5}{(Mf - a)} + b, \qquad (9)$$

The regression curve for Motif A :

$$\Delta(JND) \approx \frac{3.5}{Mf} - 1.0, \qquad (R=0.95). \qquad (10)$$

The regression curve for Motif B :

$$\Delta(JND) \approx \frac{3.5}{(Mf - 0.1)} + 1.0, \qquad (R=0.98). \qquad (11)$$

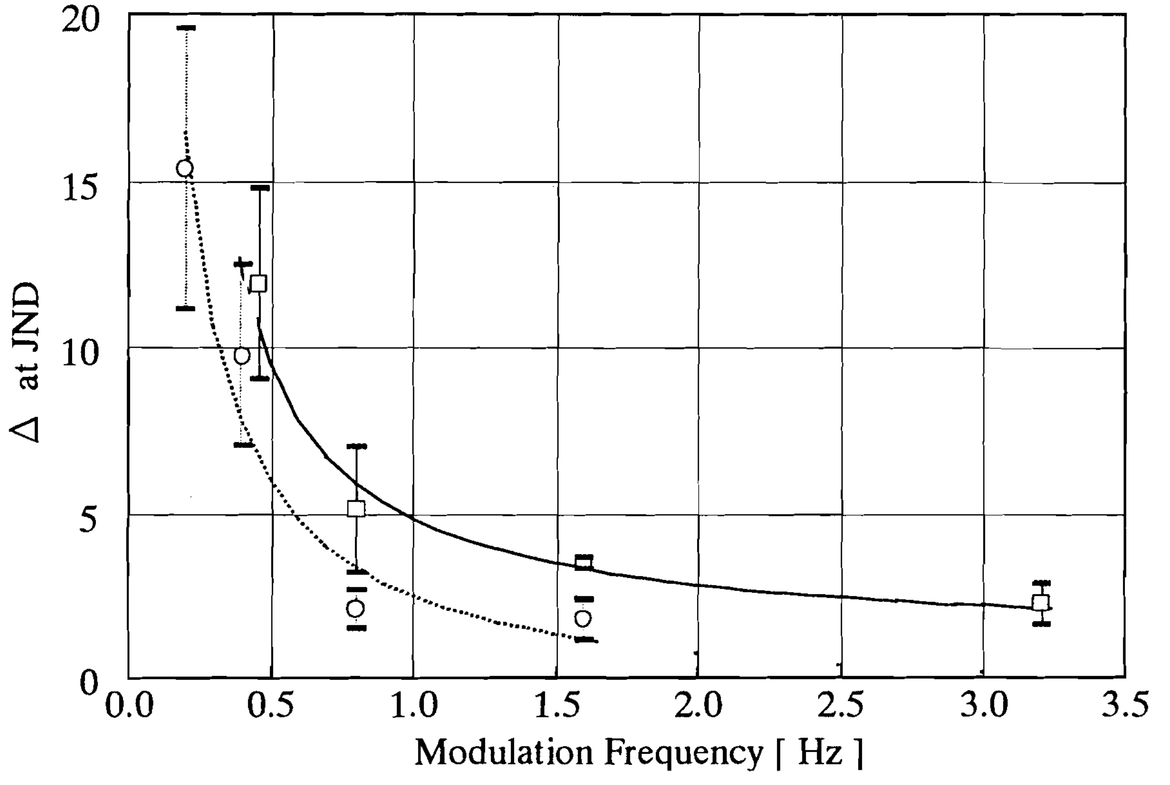


Fig. 24 The relationship between modulation frequency and ⊿ at JND.

------ : Regression curve for Motif A,

—— : Regression curve for Motif B,

: Mean and standard deviation for Motif A,

: Mean and standard deviation for Motif B.

3.5 Running τ_e of sound field

On account of making the effect of ACF of the sound field clear, τ_e of the sound stimulus was calculated. A simulation was carried out using the mean values of Δ at JND obtained experimentally. The six conditions for each Motif, 12 sound fields in all shown in Table 6 were put out in an anechoic room. The sets of data were analyzed after passing through the A-weighting network.

Figure 26 shows the result of running τ_e analysis. In general, it could be thought that the τ_e values of sound field would be longer than those of the direct sound because of the reflections. Compared with the sound field of direct sound at each time passage, τ_e of sound fields with fixed reflection become longer for each Motif. The τ_e of sound fields with Δ are relatively shorter compared to the other sound fields without modulation. A statistical homogeneity of variance is observed in a series of τ_e of sound field with Δ (JND).

Table. 6 Calculation conditions of the running τ_e and the mean values of Δat JND.

[Motif A]

Sound field	$[\Delta t_1]_p$ [ms]	Mf [Hz]	Δ (JND) [ms]
a-1	Direct sound only	----	----
a-2	120	----	----
a-3	120	0.2	15.4
a-4	120	0.4	9.8
a-5	120	0.8	2.3
a-6	120	1.6	1.8

[Motif B]

Sound field	$[\Delta t_1]_p$ [ms]	Mf [Hz]	Δ (JND) [ms]
b-1	Direct sound only	----	----
b-2	40	----	----
b-3	40	0.4	11.9
b-4	40	0.8	5.1
b-5	40	1.6	3.5
b-6	40	3.2	2.3

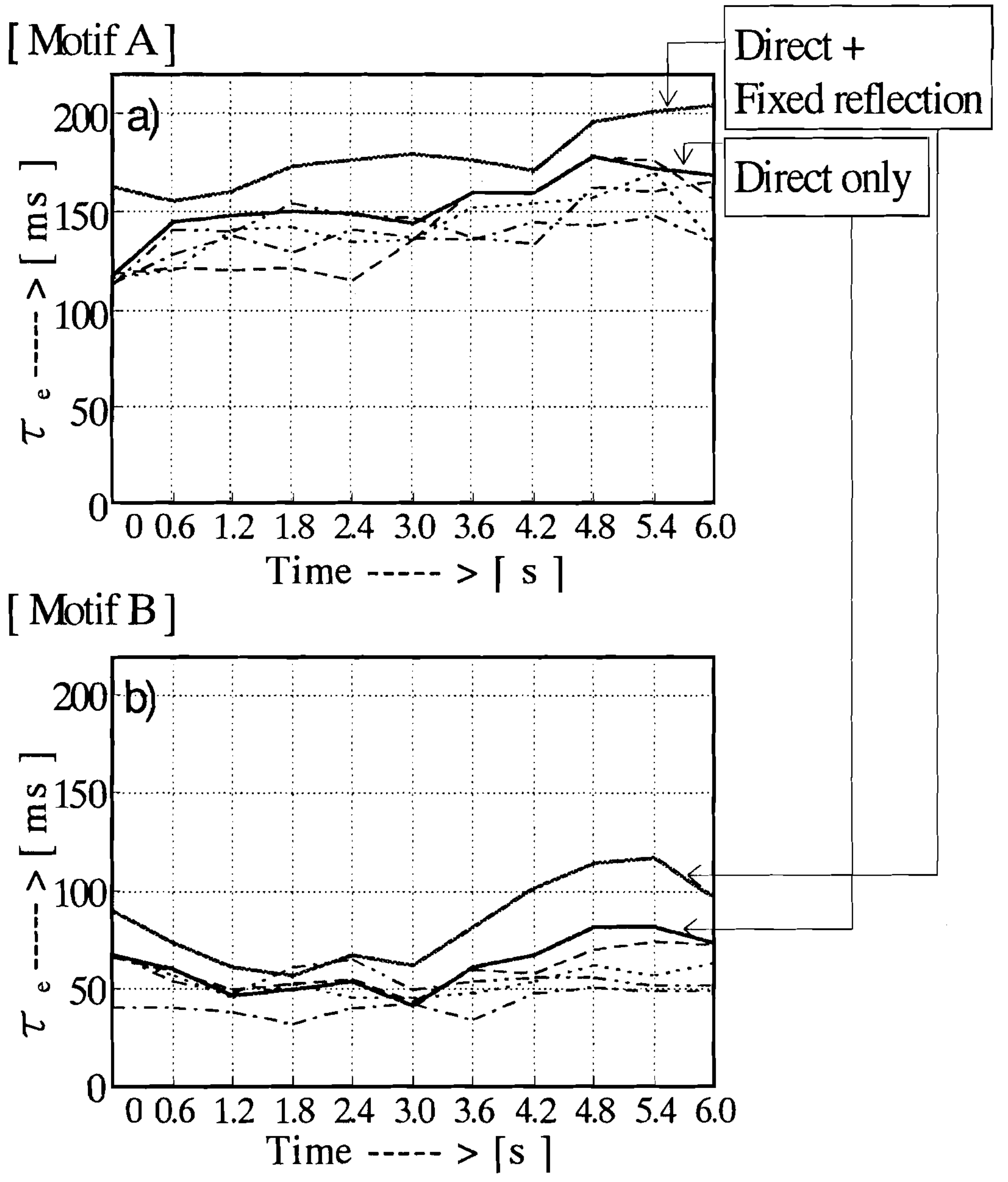


Fig. 26 Running τ_e of sound fields with and without ⊿.

a) Running τ_e of Motif A, ------- : a3, ------- : a4, ------- : a5, and -------: a6.

b) Running τ_e of Motif B, ------- : b3, ------- : b4, -------: b5, and ------- : b6.

Figure 27 shows the relationship between τ_e values of sound fields with and without Δ. A solid line indicates τ_e of sound field without Δ, and a dotted line shows the minimum τ_e with Δ (JND). The maximum difference between τ_e values of sound field without Δ and τ_e values of sound field with Δ, which may be regarded as a cue of JND are about 70ms.

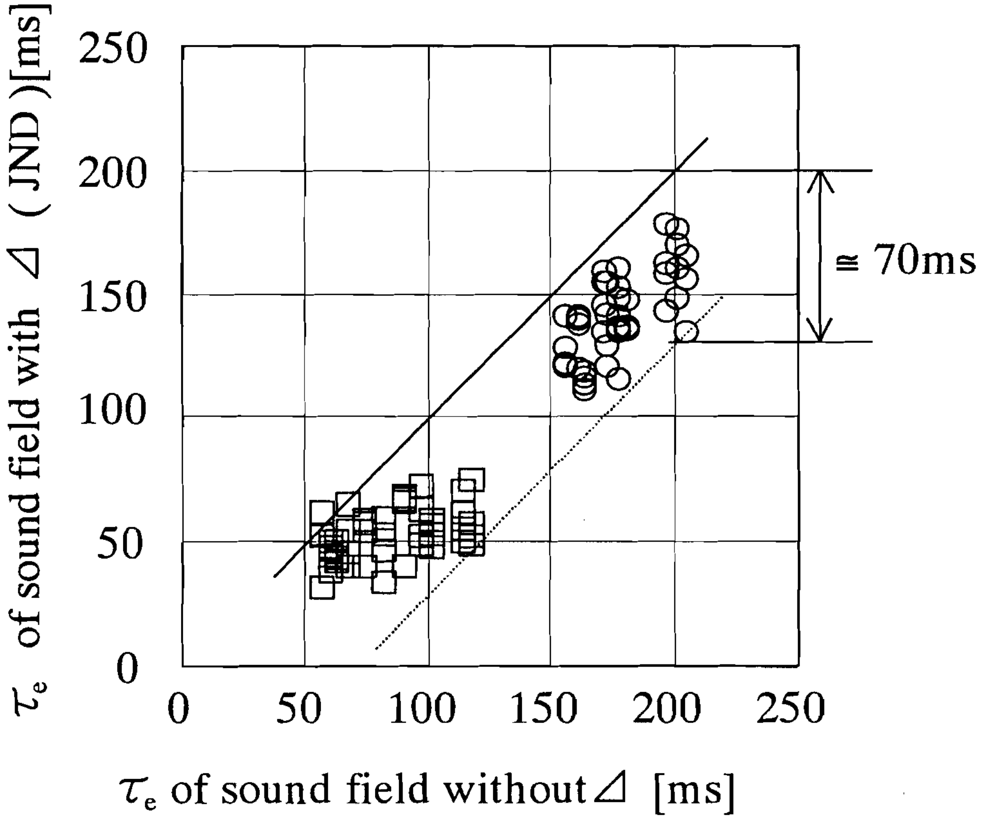


Fig. 27 The relationship between τ_e of sound fields with and without Δ at JND.

○ : τ_e at Δ_{JND} of Motif A,

□ : τ_e at Δ_{JND} of Motif B,

—— : τ_e of sound field without Δ,

------ : the shortest τ_e of sound field with Δ_{JND}.

3.6 Conclusions

From the results of the experiments, Δ_{JND} differs according to the ACF of the sound stimulus. The sound source with slower tempo (Motif A) which has longer τ_e is easier to discern than the faster tempo (Motif B). From the analysis of running τ_e using the mean values of Δ_{JND} obtained experimentally, τ_e of the sound field with Δ_{JND} is shorter than the sound field without Δ. The maximum difference of τ_e between sound field with and without Δ is about 70ms. From these results it is concluded that there is a possibility that the subjective judgment for the sound field variation is made through ACF (τ_e) as a cue.

In the experiments above, a sine wave was chosen for the variation method for Δt_1 However, from the analysed data, Δt_1 varies similarly a band-pass noise wave, JND test using octave-band as modulation pattern wave performed later. The results are shown in Appendix B.

CHAPTER Ⅳ

EFFECTS OF TIME VARIANT SOUND FIELD ON SUBJECTIVE PREFERENCE

4.1 Preface

In this chapter, the effects of fluctuations on subjective preference (psychological aspect) was examined. Concerning with the relationship between subjective preference and sound field, in the past, psychological tests relating to reverberation time (RT), delay time of the first reflection sound (Δt_1), SPL at the receiving ear (LL) and interaural cross correlation (IACC) were performed. From the results of these experiments, it was suggested that upper four parameters are relating to the sense of hearing in subjective preference, and to design of the most preferable sound field in room acoustics[1),2)3)]. So the purpose of the experiments in this section was the assertion of whether this modulation can be the one factor of subjective preference.

Two experiments were performed. In experiment 1, the delay time of the first reflection sound was varied at different delay time, and in Experiment 2, the delay time interval of the first reflection (Δ) was varied as the standard. An acoustical model of the impulse response taking account of variations of medium was used as sound stimuli. And sound stimuli were presented as a paired. For the subjective evaluation of sound field variation, the subject was asked to judge which sound field was more preferable.

From the results of Experiment 1, it was found that the relationships between scale value of preference and Δt_1 were different under conditions with and without modulation. Δt_1 that showed the peak with modulation ($[\Delta t_1]_{pm}$) became shorter than that obtained without modulation.

From the results of Experiment 2, it can be suggested that a sound field which includes time variant system has affect subjective preference in the performance of music which has a short τ_e .

4.2 The calculation method of subjective preference

The subjective response in this chapter is preference for sound fields. This method is based on the Thurstonian law of comparative judgments, and uses the linear range of the cumulative distribution function of the normal distribution. Case-V, that assumes discriminative dispersions to be equal for all stimuli, is widely known as a simplest form of the law of comparative judgment.

Table 7 illustrates typical paired comparison results with a single judgment for each pair. Wins and losses respectively are shown by the score *1* and *0* whereas a tie which may be considered for a hypothetical preference test with itself is shown by the score 0.5. Ando and Singh have described how the scale value of sound fields for each individual as follows[5].

$$S_i = \frac{\sqrt{2\pi}\left(2T_i - N\right)}{2N}, \qquad (12)$$

Where S_i denotes the scale value of sound field *i*, and T_i denotes the total score of sound field *i*, and *N* denotes the total number of sound stimulus. In this chapter, upper equation was used in order to calculate the scale value of subjective preference.

Table 7 An example of preference score sheet with *N* (the number of stimlus) = 5 .

	S_1	S_2	S_3	S_4	S_5	*Ti*	*Si*
S_1	*0.5*	*0*	*0*	*1*	*1*	*2.5*	*0.0*
S_2	*1*	*0.5*	*1*	*0*	*0*	*2.5*	*0.0*
S_3	*1*	*0*	*0.5*	*1*	*1*	*3.5*	*0.5*
S_4	*0*	*1*	*0*	*0.5*	*1*	*2.5*	*0.0*
S_5	*0*	*1*	*0*	*0*	*0.5*	*1.5*	*-0.5*

4.3 Effects on subjective preference (Experiment 1)

4.3.1 The method of experiment

Table 8 and 9 show experimental conditions. In order to observe the effects of the effective duration of the ACF (τ_e), musical sounds of differing tempos recorded in an anechoic room, were chosen as source signal. τ_e was defined by the time delay for the rectified ACF envelope dampened to 0.1. Single reflection sound field was used, and the relative amplitude of direct sound and the first reflection was made the same (Figure 23). The initial value of Δt_1 was selected around the minimum value τ_e obtained by the running τ_e analysis of each motif, which was thought to be the most preferred delay time of the first reflection, so the standards in terms of Δt_1 were different in each motif. Figure 28 shows the running τ_e of the direct sound. In Appendix C, the running τ_e of direct sound for each motif will be examined in detail.

As the modulation pattern of the delay time was considered around 0.1-~ 0.2-Hz Oct-band wave from the analysis of SPL measurement in a gymnasium, the modulation frequency (Mf) of Δt_1 was controlled simply by 0.1-Hz sine wave using a signal oscillator. Figure 29 shows a block diagram of the experimental set-up.

There were ten stimuli in each motif, (five standards for Δt_1 by two standards, that were with and without modulation). The stimuli were paired, and the subjects judged which sound field was more preferable. In the experiment, presentation of the sound stimulus was repeated 8 times for each subject.

Table. 8 Experimental conditions.

Items	Synopsis
Sound source of stimuli	Motif A: Royal Pavane by Gibbons Motif B: Sinfonietta by Malcom Arnold
The delay time of the first reflection Δt_1 [ms]	Motif A: 40, 60, 80, 120, 160 Motif B: 30, 40, 60, 80, 100
Modulation method (MM)	a) without modulation b) with modulation by sine wave
Modulation frequency (MF)	0.1-Hz
Modulation interval Δ [ms]	Motif A : 24.0 Motif B : 30.4
Subjects	Two female and two male of the ages between 22 and 30 years old
The presentation procedure of the paired stimulus	stimulus A) ------------- (6 seconds) interval ------------- (1 seconds) stimulus B) ------------- (6 seconds) selection interval -------- (2 seconds) for judging the sound field which was more preferable.

Table.9 The experimental conditions of sound stimulus.

Number of sound stimulus	Motif A Δt_1 [ms]	Motif A Modulation	Motif B Δt_1 [ms]	Motif B Modulation
1	40	Without	30	Without
2	60	Without	40	Without
3	80	Without	60	Without
4	120	Without	80	Without
5	160	Without	100	Without
6	40	With	30	With
7	60	With	40	With
8	80	With	60	With
9	120	With	80	With
10	160	With	100	With

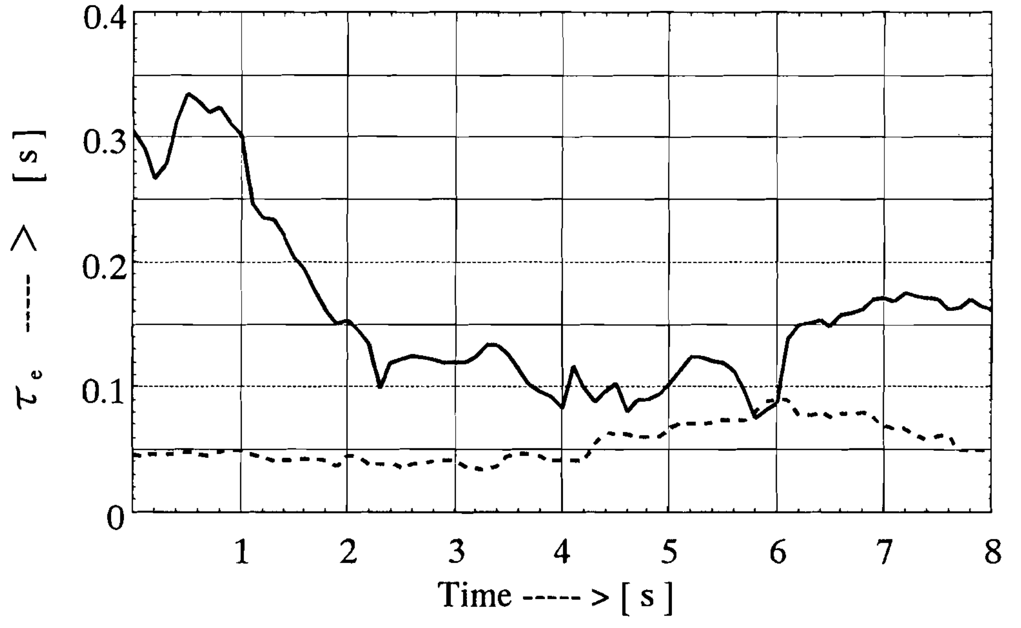


Fig. 28 Running τ_e of direct sound source.
(A line shows the running τ_e of Motif A, dotted line of Motif B.)

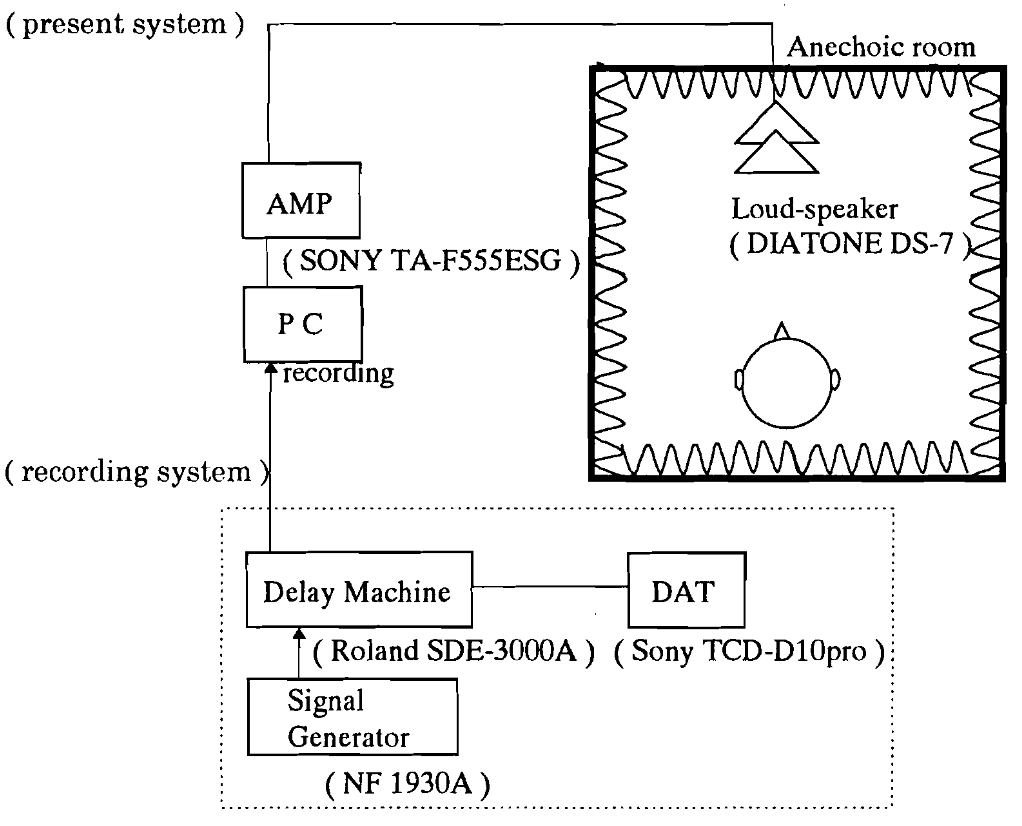


Fig. 29 A block diagram of experimental set-up.

4.3.2 Results and discussions

Figure 30, 31, 32 and 33 and Figure 35, 36, 37 and 38 show relationships between subjective preference of each subject and Δt_1 with and without modulation of each motif. Figure 34 and 39 show mean scale value and ± 1 SD of all 4 subjects in each motif. Table 30, 31, 32, 33, 34, 35, 36, 37, 38 and 39 show results of one-way analysis of variance for upper figures.

As for Motif A as the sound source, scale values with modulation of delay time in subject FF were rather smaller than that without modulation of delay time in Figure 32. Scale values with modulation in subjects MS and FI were relatively larger than that without modulation at the range of short Δt_1 in Figure 31 and 33. The delay times at the maximum scale value of subjective preference without modulation were 60 or 120 ms, while that with modulation was 80 ms, excluding subject FI.

As for Motif B as the sound source, scale values with and without modulation of either subject were intersected mutually. The delay times at the peak scale value without modulation were 40 or 60 ms, while that with modulation varied from 30 to 60 ms. The specific difference was not found in the individual difference at each delay time in both cases and motifs.

From Figure 34 and 39, it was found that the standard deviation of scale value with modulation was relatively larger than that without modulation. The Δt_1 showing the peak scale values with modulation was shorter than that without modulation in both motif A and B. The most preferred delay time ($[\Delta t_1]_p$ and $[\Delta t_1]_{pm}$) was derived from each regression curve of Figure 34 and 39, as shown in Table 20.

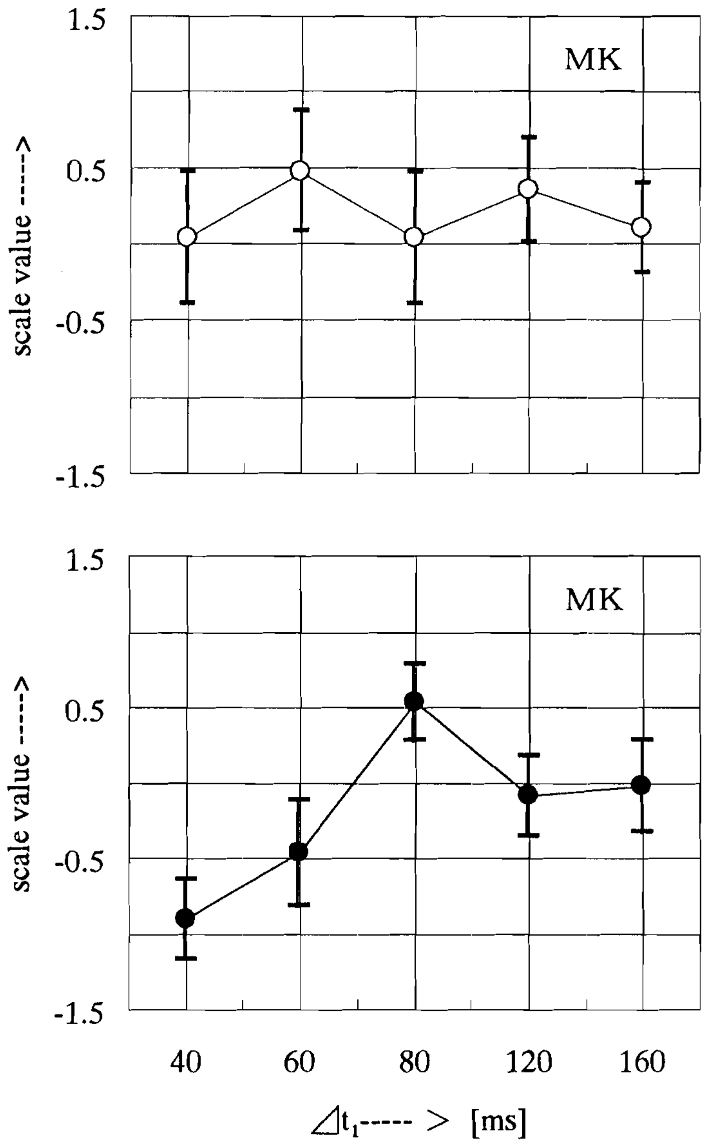


Fig.30 The relationship between scale value of subject MK for Motif A and Δt_1 (Upper: without modulation, below: with modulation).

Table.10 Result of one-way analysis of variance for upper figure (*: $p< 0.05$, **: $p< 0.01$).

	1	2	3	4	5	6	7	8	9	10
1		*				**	**	**		
2			*		*	**	**		**	**
3						**	**	**		
4						**	**		*	*
5						**	**	*		
6							*	**	**	**
7								**	*	*
8									**	**
9										
10										

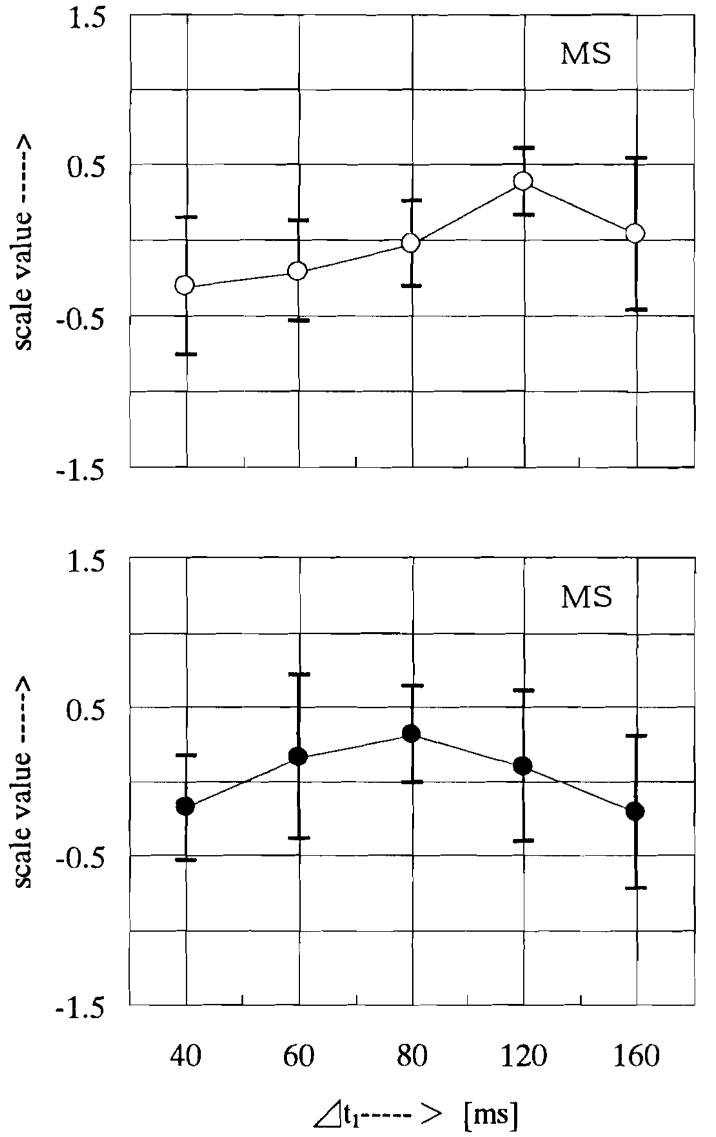


Fig.31 The relationship between scale value of subject MS for Motif A and $\varDelta t_1$ (Upper : without modulation, below : with modulation).

Table 11 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	1	2	3	4	5	6	7	8	9	10
1				**			*	**		
2				**				*		
3										
4						**				**
5										
6								*		
7										
8										*
9										
10										

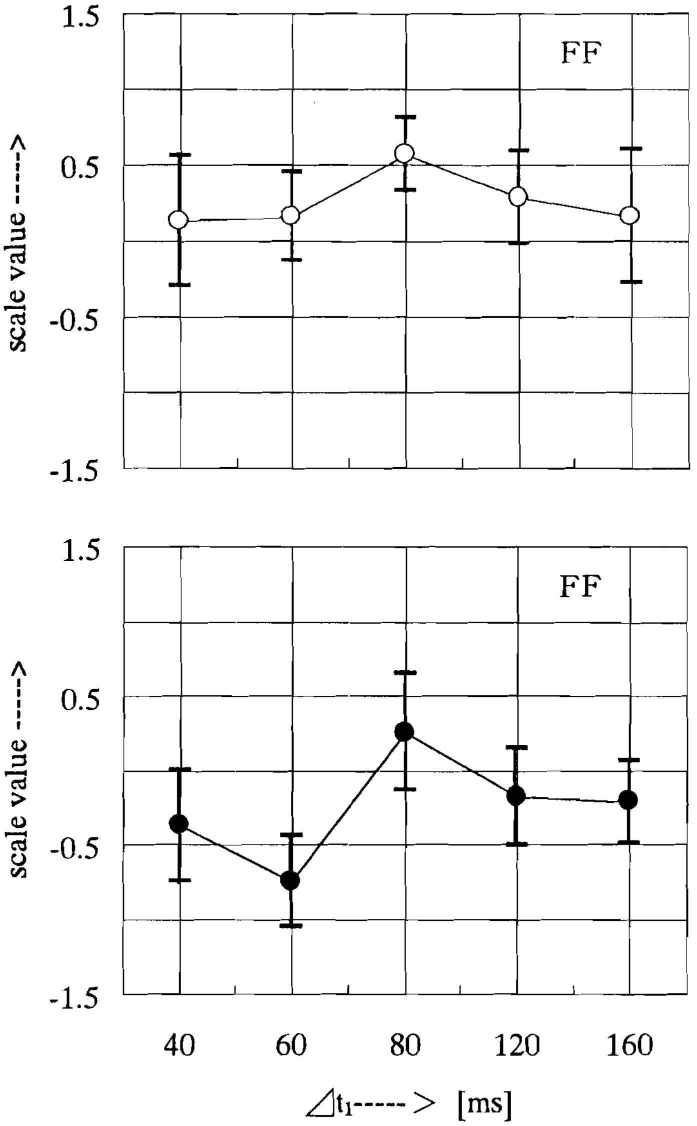


Fig.32 The relationship between scale value of subject FF for Motif A and ∠t_1 (Upper : without modulation, below : with modulation).

Table 12 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	1	2	3	4	5	6	7	8	9	10
1			*			**	**			
2			*			**	**			*
3					*	**	**		**	**
4										
5						**	**			*
6							*	**		
7								**	**	**
8									*	*
9										
10										

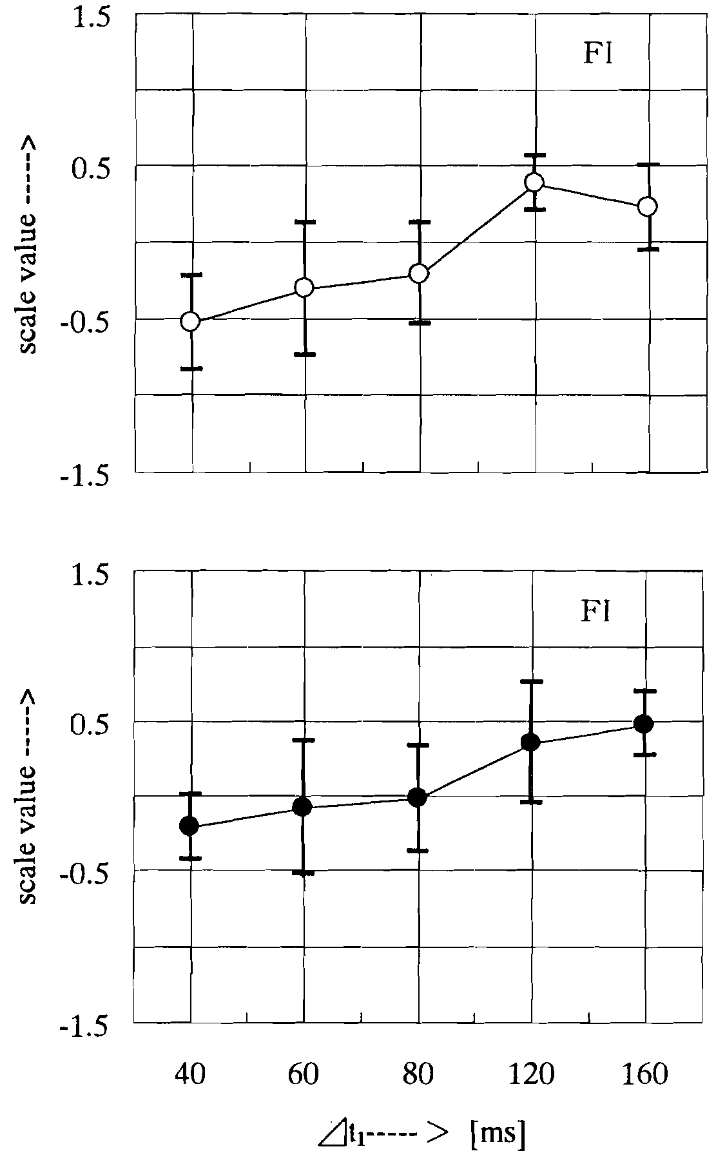


Fig.33 The relationship between scale value of subject FI for Motif A and $\varDelta t_1$ (Upper : without modulation, below : with modulation).

Table 13 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	1	2	3	4	5	6	7	8	9	10
1				**	**		*	**	**	**
2				**	**				**	**
3				**	*				**	**
4						**	**	*		
5						*				
6									**	**
7									*	**
8									*	**
9										
10										

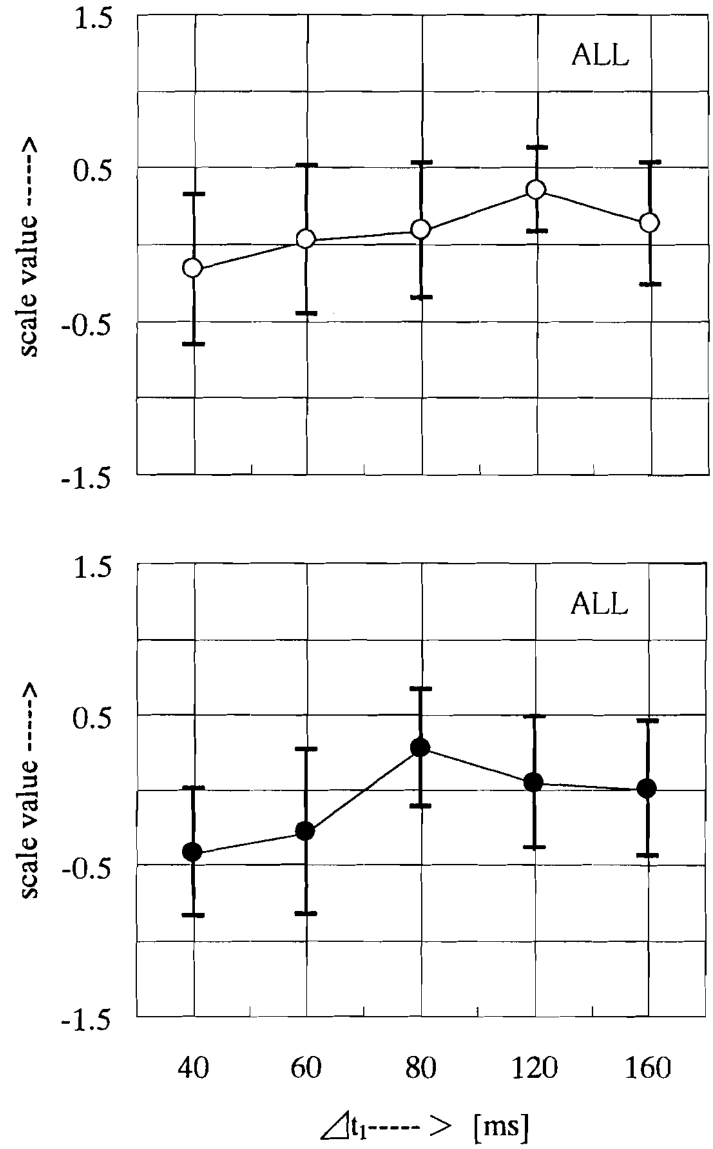


Fig.34 The relationship between scale value of all subjects for Motif A and Δt_1 (Upper : without modulation, below : with modulation).

Table 14 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	1	2	3	4	5	6	7	8	9	10
1			*	**	**	*		**		
2				**		**	**	*		
3				*		**	**			
4					*	**	**		**	**
5						**	**			
6								**	**	**
7								**	**	**
8									*	*
9										
10										

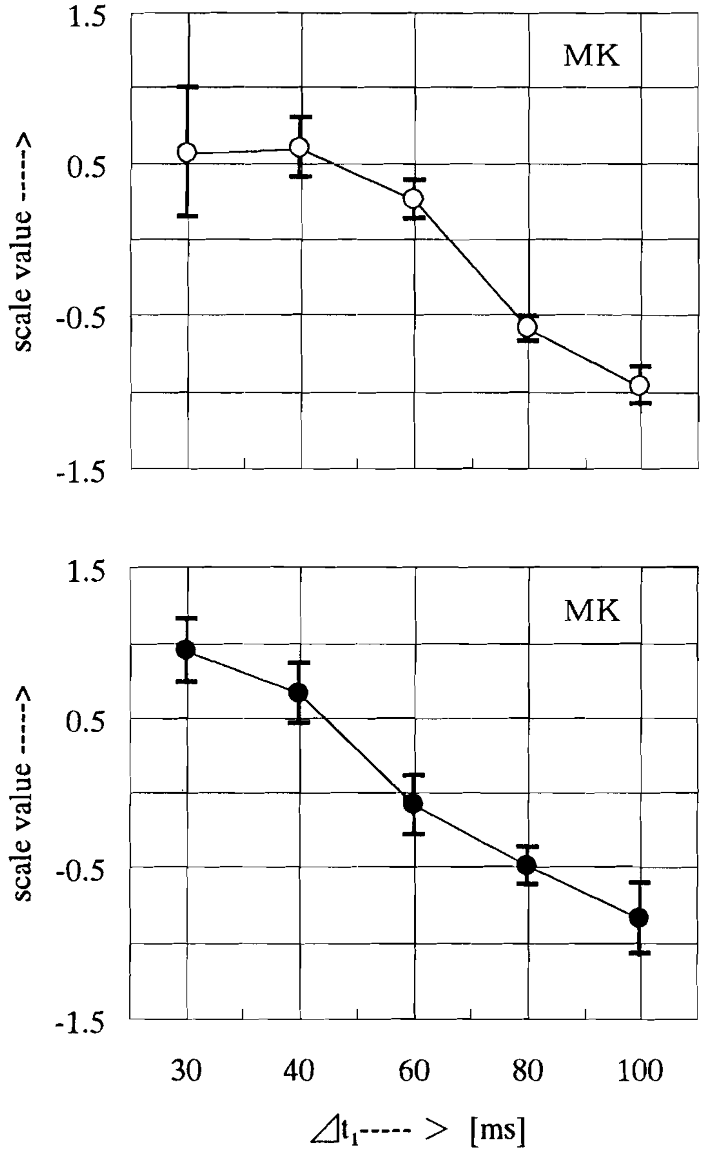


Fig.35 The relationship between scale value of subject MK for Motif B and $\varDelta t_1$ (Upper : without modulation, below : with modulation).

Table 15 Result of one-way analysis of variance for upper figure (*: $p< 0.05$, **: $p< 0.01$).

	1	2	3	4	5	6	7	8	9	10
1			**	**	**	**		**	**	**
2			**	**	**	**		**	**	**
3				**	**	**	**	**	**	**
4					**	**	**	**		*
5						**	**	**	**	
6							*	**	**	**
7								**	**	**
8									**	**
9										**
10										

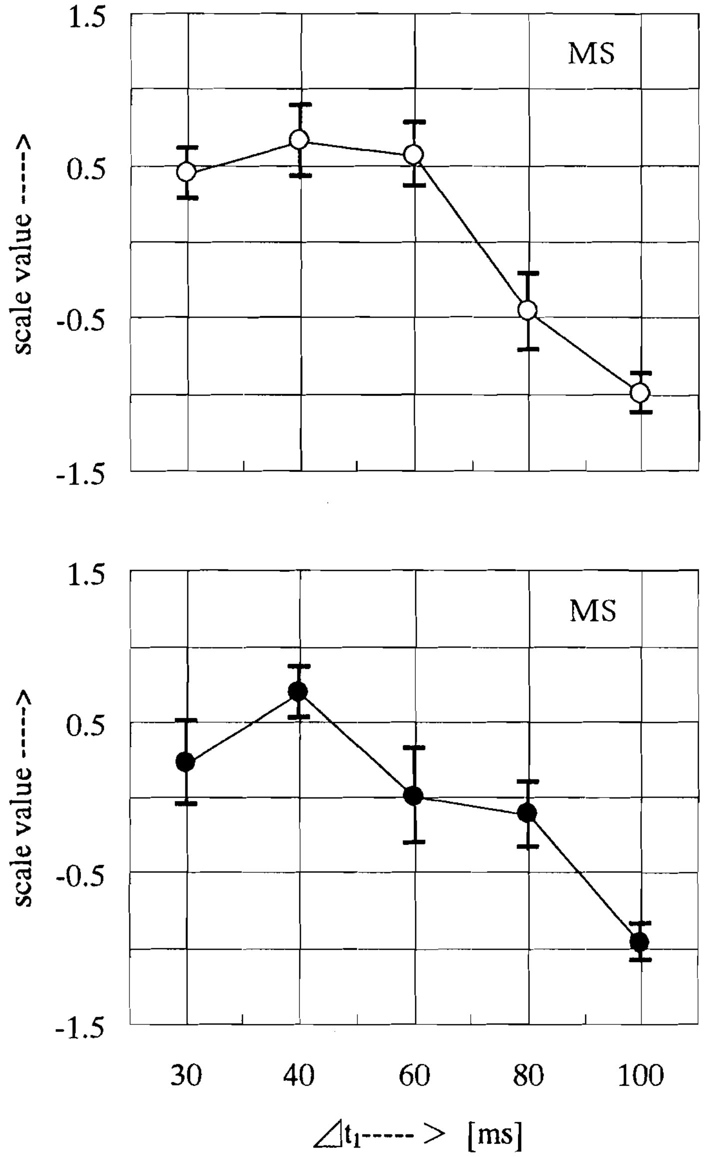


Fig.36 The relationship between scale value of subject MS for Motif B and Δt_1 (Upper: without modulation, below : with modulation).

Table 16 Result of one-way analysis of variance for upper figure (*: $p< 0.05$, **: $p< 0.01$).

	1	2	3	4	5	6	7	8	9	10
1				**	**		*	**	**	**
2				**	**	**		**	**	**
3				**	**	**		**	**	**
4					**	**	**	**	**	**
5						**	**	**	**	
6							**		**	**
7								**	**	**
8										**
9										**
10										

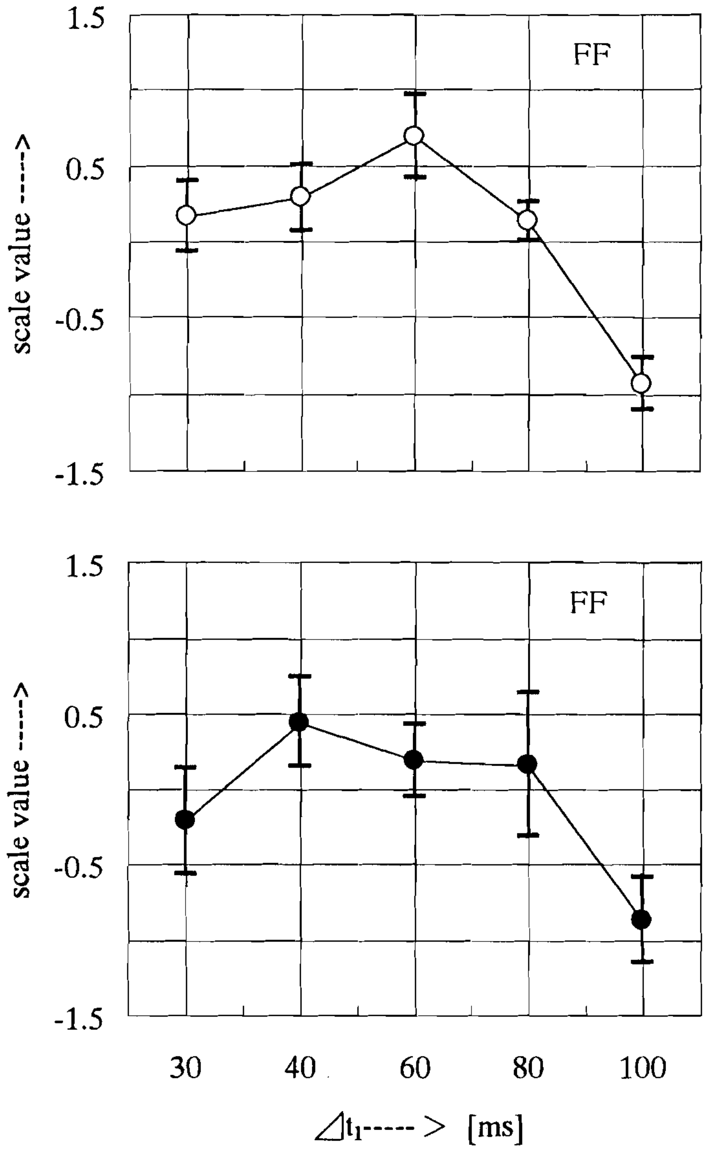


Fig.37 The relationship between scale value of subject FF for Motif B and $\varDelta t_1$ (Upper : without modulation, below : with modulation).

Table 17 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	1	2	3	4	5	6	7	8	9	10
1			**		**	*				**
2			**		**	**				**
3				**	**	**		**	**	**
4					**	*	*			**
5						**	**	**	**	
6							**	**	*	**
7										**
8										**
9										**
10										

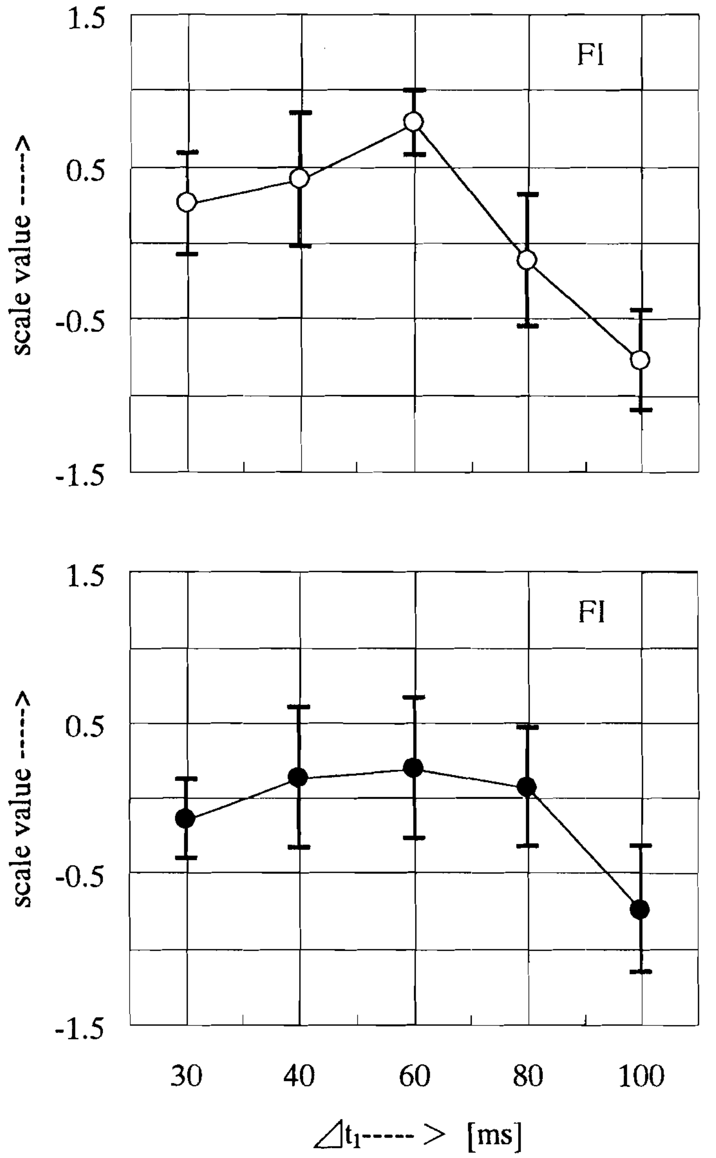


Fig.38 The relationship between scale value of subject FI for Motif B and ⊿t_1 (Upper : without modulation, below : with modulation).

Table 18 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	1	2	3	4	5	6	7	8	9	10
1			*		**					**
2				*	**	**				**
3				**	**	**	**	**	**	**
4					**					**
5						**	**	**	**	
6										**
7										**
8										**
9										**
10										

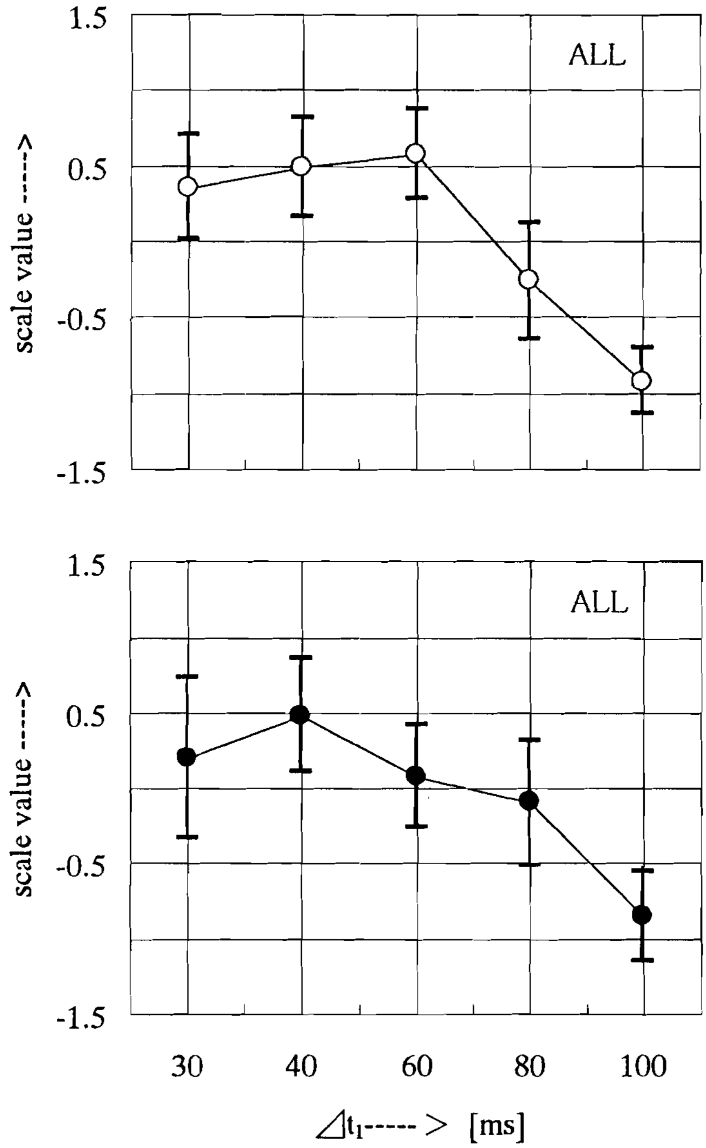


Fig.39 The relationship between scale value of all subjects for Motif B and $\varDelta t_1$ (Upper: without modulation, below: with modulation).

Table 19 Result of one-way analysis of variance for upper figure (*: $p< 0.05$, **: $p< 0.01$).

	1	2	3	4	5	6	7	8	9	10
1			*	**	**			**	**	**
2				**	**	**		**	**	**
3				**	**	**		**	**	**
4					**	**	**	**		**
5						**	**	**	**	
6							**		**	**
7								**	**	**
8										**
9										**
10										

Figure 40 shows the relationship between normalized Δt_1 by $[\Delta t_1]_p$ and the scale value. From previous experiments, scale value can be expressed in equation (12).

$$S \approx -\alpha |x|^{3/2}, \qquad (13)$$

Then,

$$x = \log_{10}(\Delta t_1 / [\Delta t_1]_p), \qquad (14)$$

Different numbers of α values depending on the cases of with or without modulation are given as follows.

(Without modulation)

$$\alpha = \begin{cases} 1.8 & (0 \geq x) \\ 6.5 & (0 < x) \end{cases}, \qquad (15)$$

(With modulation)

$$\alpha = \begin{cases} 3.0 & (0 \geq x) \\ 3.4 & (0 < x) \end{cases}, \qquad (16)$$

In the range of $x < 0$, i.e. $\Delta t_1 < [\Delta t_1]_p$, the degree of inclination curve without modulation became small. On the contrary, in the range of $x > 0$, i.e. $\Delta t_1 > [\Delta t_1]_p$, the degree of inclination curve with modulation become smaller.

Table. 20 $[\Delta t_1]_p$ obtained by regression curves in figure 34 and 39.

Sound source	$[\Delta t_1]_p$ [ms]
Motif A	without modulation : 119
	with modulation : 103
Motif B	without modulation : 44
	with modulation : 34

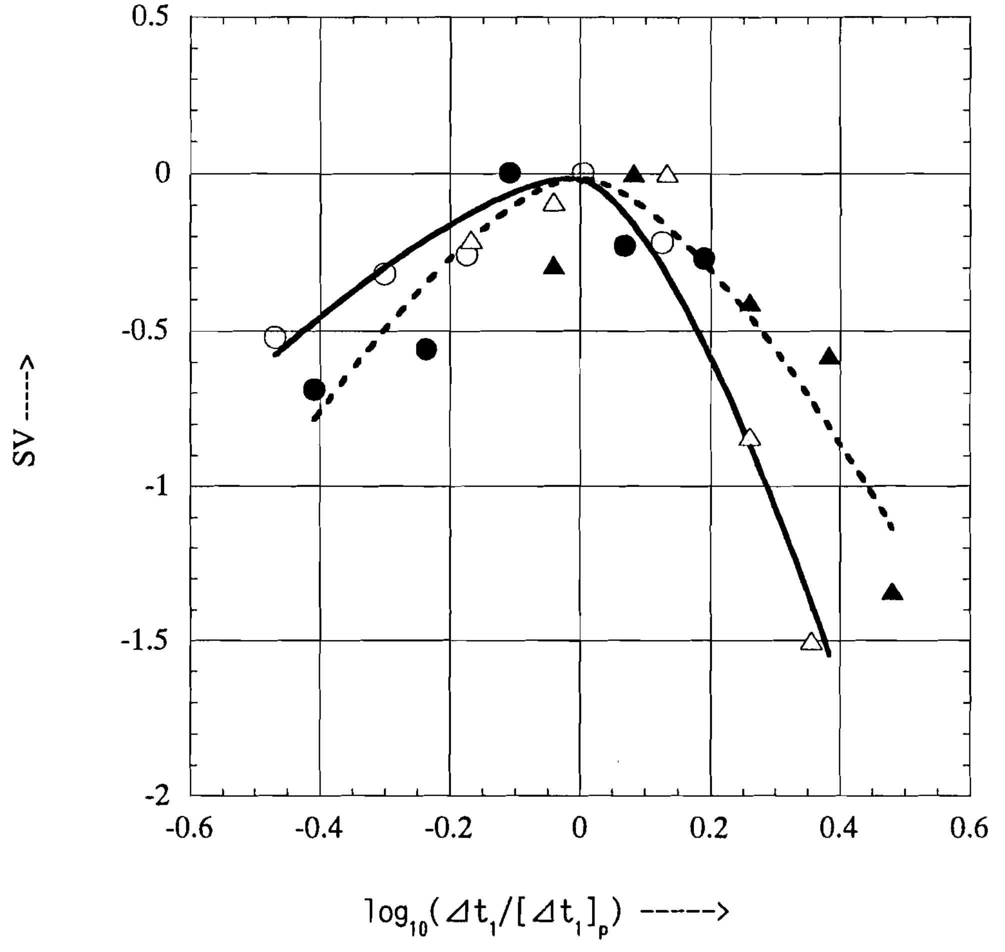


Fig. 40 The relationship between Δt_1 / $[\Delta t_1]_p$ and scale value of subjective preference. (O: scale values of subjective preference without modulation, ●: scale values with modulation, line shows the regression curve for O, dotted curve for ●.)

4.4 Effects on subjective preference (Experiment 2)

4.4.1 The method of experiment

In this experiment, musical sound sources Motif A and B, shown in Table 8 were also used as sound sources. Fluctuation of sound field is simulated by simple impuluse response which is consists of the direct sound and the single reflection whose arrival time was varied cyclically, as utilized before and shown in Figure 23 with definitions. The relative amplitude (A_r/A_d) of direct sound and reflection sound was fixed at the constant value. The initial delay time (Δt_1) was adjusted to the most preferred delay time of reflection which was obtained in the previous experiment for each motif. Table 21 shows the experimental conditions in terms of initial delay time of the first reflection (Δt_1) and modulation interval of delay time (Δ). Six standards of the modulation interval (Δ) were set. Each Δ was chosen around the values of just noticable difference, JND.

Though it was assumed that octave band waves were thought to be the modulation pattern in Chapter II, the modulation of delay time was controlled by the sine wave. The modulation frequency, 0.1-Hz, was decided because it is actually expected to be 0.1-~0.2-Hz, which was observed in the examination of SPL change.

The duration of the sound stimulus was set in about 8 seconds interval, and the paired stimuli were presented. Subjects, aged from 22 to 30, were asked which of two stimuli more preferable was. Four subjects participated. A block diagram of the experimental set-up which was the same system of section 4.3 is shown in Figure 29.

Table 9. Experimental conditions in terms of initial delay time (Δt_1) and modulation interval (Δ) of delay time, and showing sound field number.

[Motif A]

Number of sound field	The initial delay time of the first reflection [ms]	Δ [ms]	Modulation of delay time
1	120	0.0	Without
2	120	8.0	With
3	120	16.0	With
4	120	24.0	With
5	120	32.0	With
6	120	40.0	With

[Motif B]

Number of sound field	The initial delay time of the first reflection [ms]	Δ [ms]	Modulation of delay time
1	60	0.0	Without
2	60	15.2	With
3	60	30.4	With
4	60	45.6	With
5	60	60.8	With
6	60	70.9	With

4.4.2 Results and discussions

Figure 41, 42, 43 and 44 shows the relationship between scale value of subjective preference for each subject and modulation interval (Δ). Figure 45 shows the relationship between modulation interval and the mean scale value of subjective preference. Table 22 shows the result of one-way analysis of variance for Figure 45.

From Figure 41, 42, 43 and 44, three subjects (MK, FF and FO) of four subjects for Motif A and three subjects (MS, FF and FO) for Motif B preferred the stimuli with modulation of delay time rather than that without fluctuation.

From Figure 45, it can be seen that scale value with modulation is bigger than that without modulation in both Motif A and B. From the regression curves of this figure, the modulation interval of delay time showing the maximum value of subjective preference is about 0 ms, it means without modulation, for Motif A, and is about 13 ms for Motif B, that is with modulation. There is significant difference ($p<0.05$) between sound stimulus 1 (without modulation) and 2 (with modulation) in the case of Motif B. There is no significant difference in the case of Motif A.

In conclusion, it is suggested that a sound field which includes a time-variant system might have a better effect on subjective preference in the performance of music which has a short τ_e.

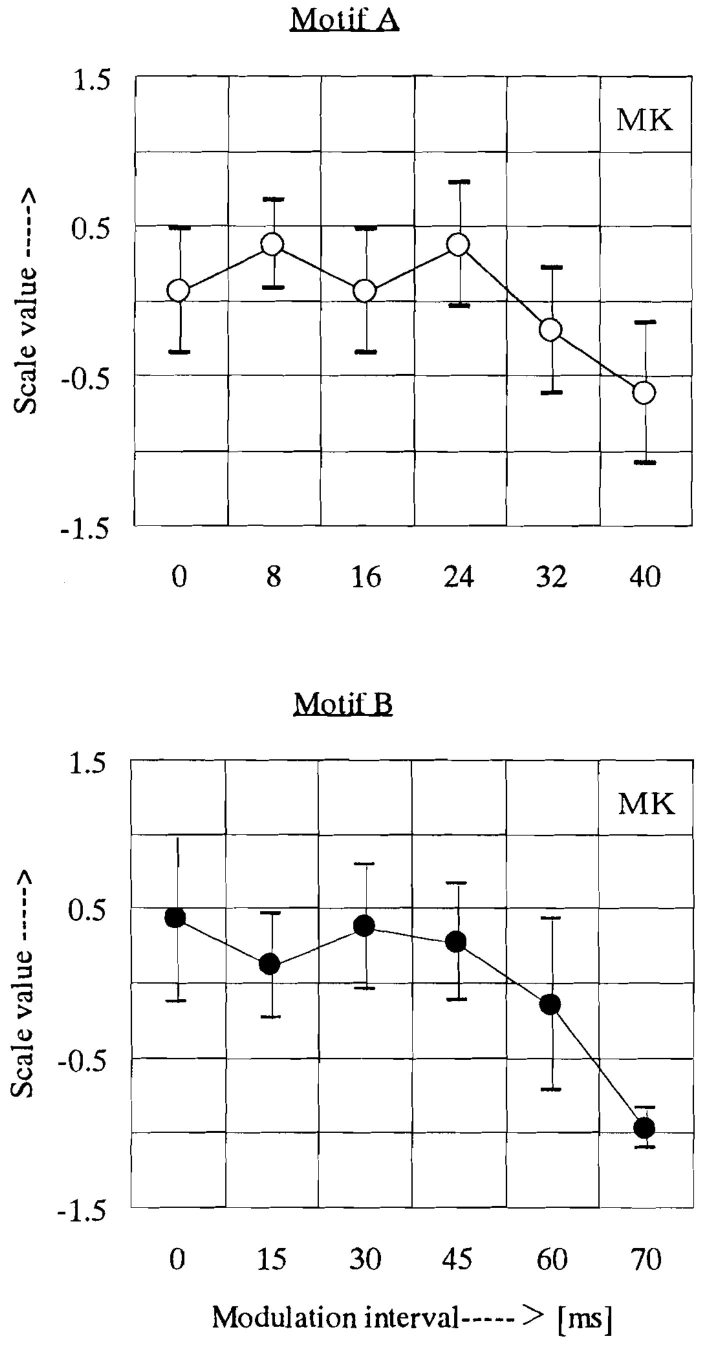


Fig. 41 The relationship between scale value of subjective preference for subject MK and modulation interval of delay time (Upper: Motif A, Lower: Motif B, black and white circle: mean scale value at each modulation interval, upper and lower line: $\pm$1SD).

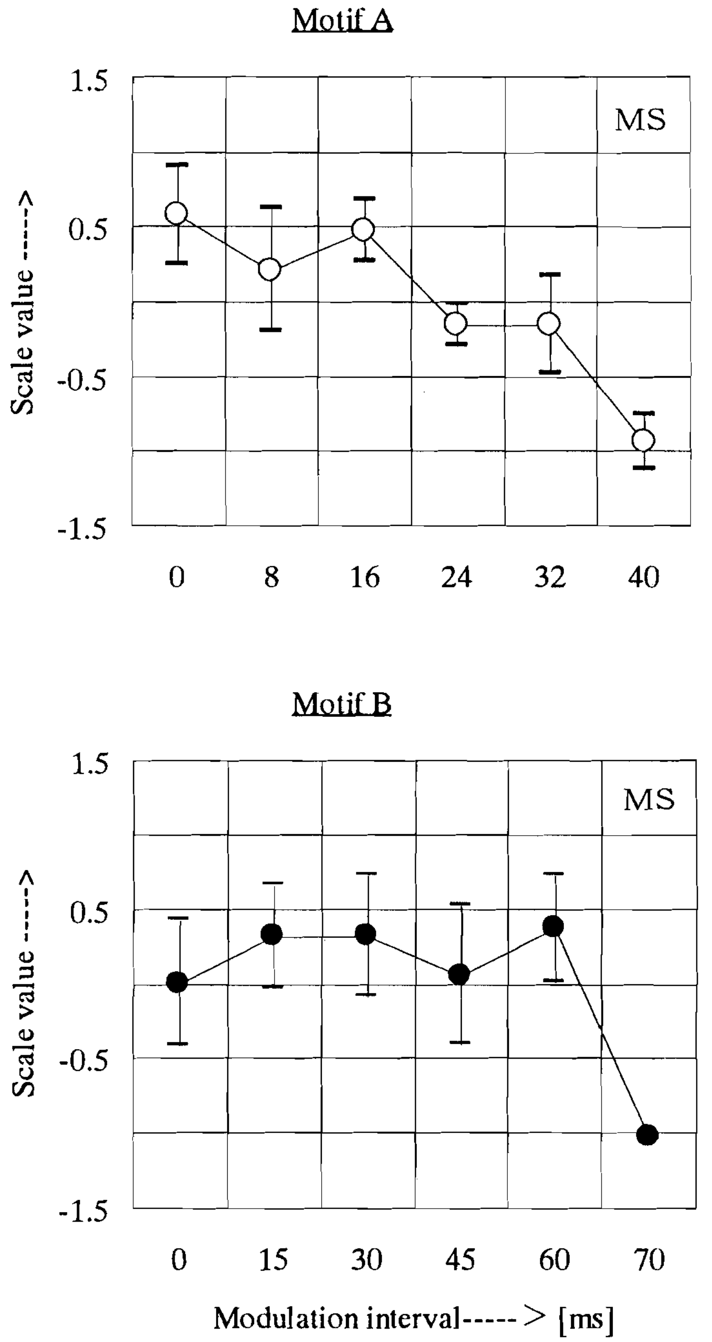


Fig. 42 The relationship between scale value of subjective preference for subject MS and modulation interval of delay time (Upper: Motif A, Lower: Motif B, black and white circle: mean scale value at each modulation interval, upper and lower line: ±1SD).

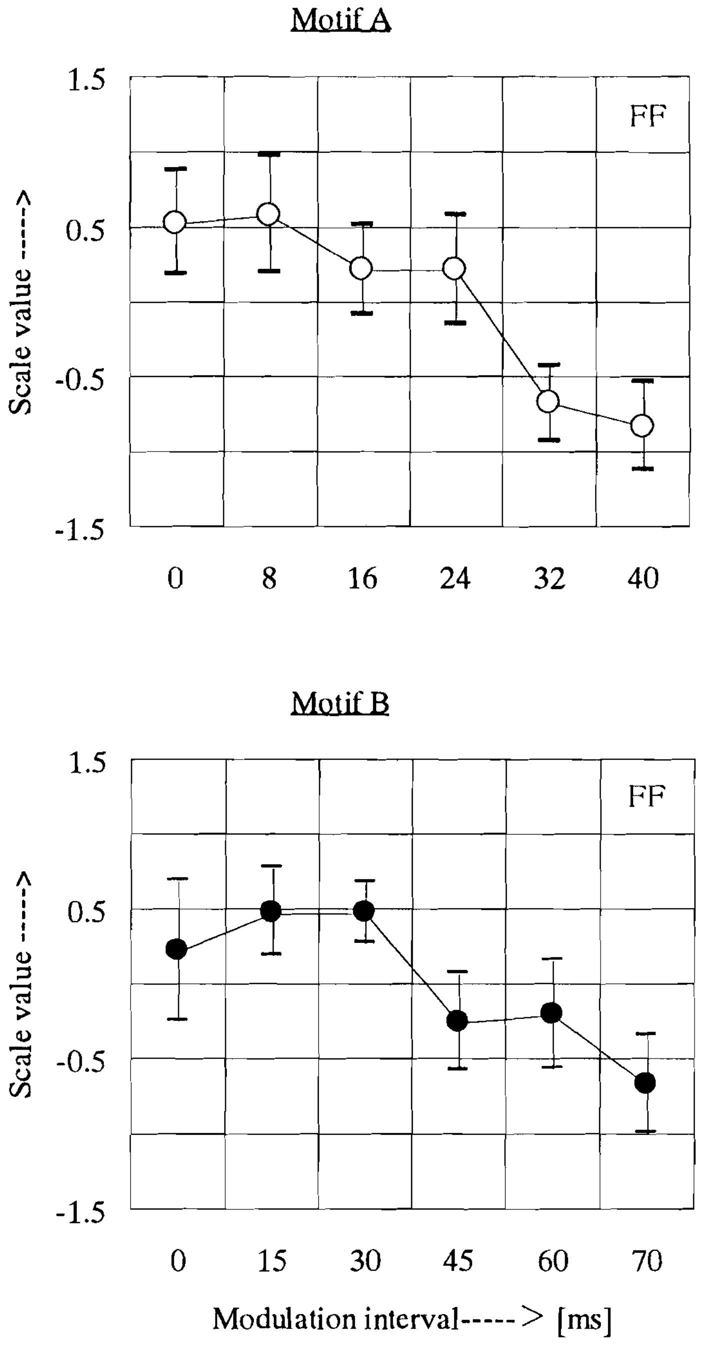


Fig. 43 The relationship between scale value of subjective preference for subject FF and modulation interval of delay time (Upper: Motif A, Lower: Motif B, black and white circle: mean scale value at each modulation interval, upper and lower line: ±1SD).

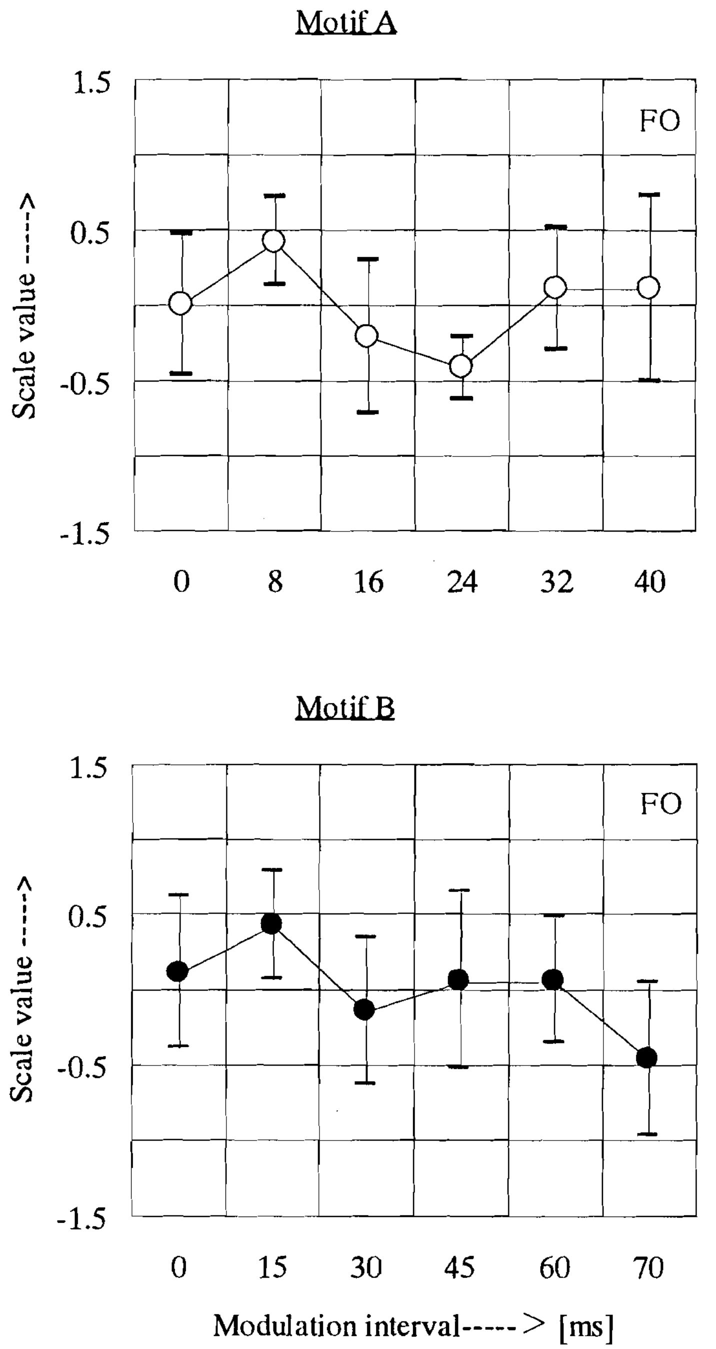


Fig. 44 The relationship between scale value of subjective preference for subject FO and modulation interval of delay time (Upper: Motif A, Lower: Motif B, black and white circle: mean scale value at each modulation interval, upper and lower line: $\pm$1SD).

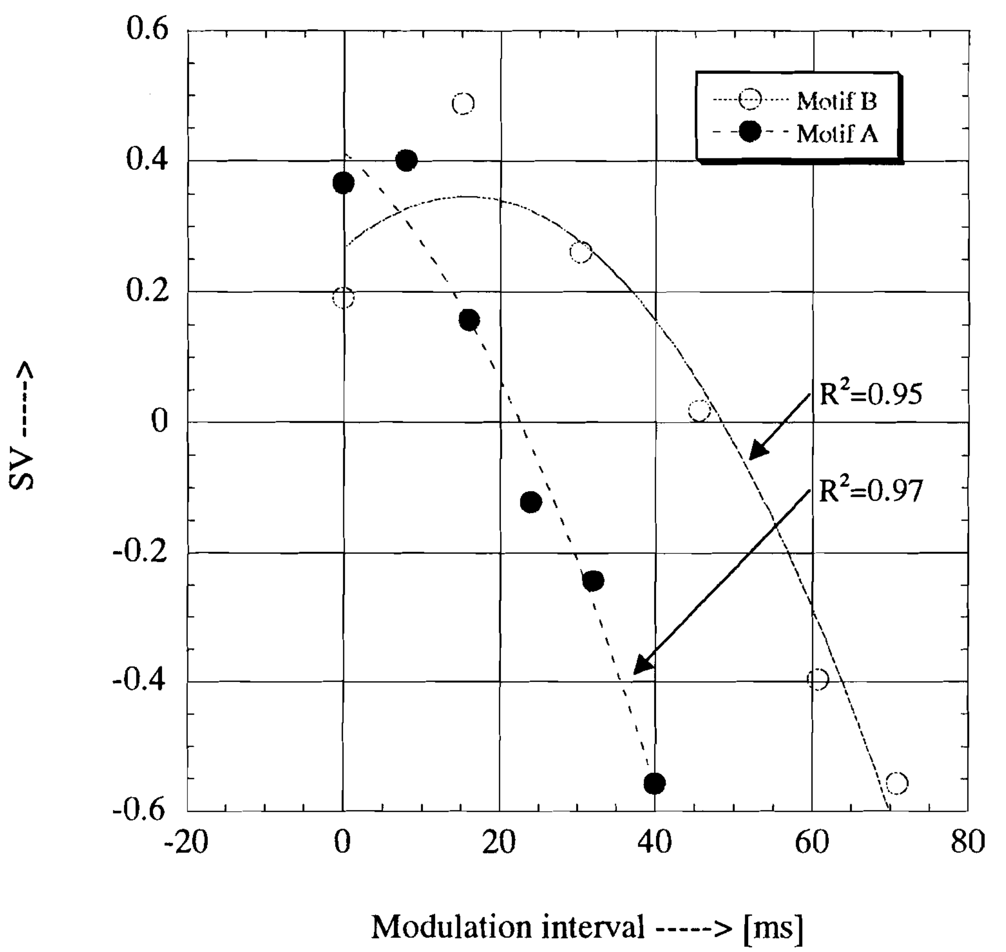


Fig. 45 The relationship between Δ and mean scale value of all three subjective.(O shows mean scale value of Motif A, ● shows of Motif B.)

-------- : regression curve for Motif A, $SV = -0.00035(\Delta - 22.6)(\Delta + 52.3)$

——— : regression curve for Motif B, $SV = -0.00032(\Delta - 50.4)(\Delta + 13.4)$

Table 22 Result of one-way analysis of variance for upper figure (*: p< 0.05, **: p< 0.01).

	Motif A						Motif B					
	1	2	3	4	5	6	1	2	3	4	5	6
1					*	**		*				**
2					*	**				**	*	**
3						**				*		**
4						*						**
5												**
6												

4.5 Conclusions

From the results of Experiment 1, it was found that $[\Delta t_1]_p$, which was obtained from a paired comparison test, was shortened by adding the modulation to the delay-time of the first reflection. It was also found that the regression curve from the figure that was plotted by $[\Delta t_1]_p$ differed between the two cases, that were with and without modulation. When $\Delta t_1 < [\Delta t_1]_p$, the scale value without modulation became bigger than that with modulation, and at $\Delta t_1 > [\Delta t_1]_p$, scale value with modulation become bigger than that without modulation.

From the results of Experiment 2, it can be seen that scale value with modulation is bigger than that without modulation in both Motif A and B. From the regression curves of this figure, the modulation interval of delay time showing the maximum value of subjective preference is about 0 ms (without modulation) for Motif A, and is about 13 ms for Motif B, that is with modulation. There is significant difference ($p<0.05$) between sound stimulus 1 (without modulation) and 2 (with modulation) in the case of Motif B.

In conclusion, it is suggested that a sound field which includes a time-variant system might have a better effect on subjective preference in the performance of music which has a short τ_e. In this two experiments, a sine wave was utilized as the modulation method of the first reflection.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary and Conclusions

In Chapter I, previous studies of time variant system and aim of these studies are summarized. These studies focused on physical and psychological aspects of time variant system in room acoustics.

With respect to outdoor sound propagation, time variants such as fluctuation or modulation of sound pressure level were taken into consideration in many studies. Issues of room acoustics have been discussed on the basis of steady state sound fields, and time variants have been mostly ignored. But the movements of a player and audience and the environmental changes could be regarded as time varying system effecting on the sound transmission in room acoustics.

In order to make effects of this fluctuation clear, the study was conducted as follows.

First of all, the relation between changes of the sound transmission function in a room and indoor environmental change such as air currents and temperature gradients were examined physically in order to clarify the mechanism of the fluctuation.

Then, the psychological tests were performed in order to observe the effect of the fluctuation on subjective preference. The time variant model, which was discussed in the physical examination, was used for these tests.

In Chapter II, the feature of fluctuation of sound pressure level (SPL) was examined with the data measured in a gymnasium. From the features, an acoustical model including time fluctuation was devised.

First of all, SPL produced by a pure tone (500-Hz ～ 16-kHz) were compared with the air conditioning system on and off. SPL change was clearly observed at frequencies higher than 2-kHz, when the air conditioning was on. As the frequency increased, SPL change became stronger. The mean standard deviation of SPL change of all observation points was about 0.9 dB at 2 kHz, 2.5 dB at 4 kHz, 3.3 dB at 8 kHz, and 3.8 dB at 16 kHz. From a statistical analysis of the amplitude change, its cumulative frequency curve was identified as Nakagami-Rice distribution. Thus, it was concluded that SPL change was related to the composition of a regular component and irregular components.

Accordingly, it was supposed that the impulse response consisted of the direct sound (regular) and the changing delay-time of the reflection sound (irregular). From examination of the formula, statistical characteristic of this model was found to have Nakagami-Rice distribution.

Next, SPL was simulated by using this model in order to compare actual sound fields. The cumulative frequency curve of amplitude change by SPL simulation fitted to Nakagami-Rice distribution.

In Chapter III, the effects of fluctuations on subjective judgment (a psychological aspect) was examined. The just noticeable difference (JND) of the colouration produced by the delay-time modulation of the first reflection was measured in order to identify effects on subjective judgments and the psychological standards for subjective preference.

The common experimental conditions in Chapter III and IV were as follows. The sine waves of several frequencies were selected as modulation pattern. Sound stimulus consists of the direct sound and the first reflection sound. Motif A and B having different effective duration (τ_e) of auto-correlation function (ACF), were used as sound sources.

In this experiment, subjects judged JND of clouration by means of adjusting the modulation interval (Δ) of the first reflection delay-time. From results of the experiment, the JND of Δ increased as the modulation frequency decreased. The JND of Δ for Motif A (the slower tempo sound source) was smaller than that of Motif B (the faster tempo sound source). In this experiment, the running τ_e of stimuli was also analyzed. In general, τ_e of a single reflection sound field becomes longer than that of a direct sound field, but τ_e with modulation of delay time becomes shorter than that without modulation. The maximum difference between the τ_e values of sound field with and without Δ, which may be regarded as a clue of JND, was about 70 ms.

Chapter IV describes two experiments in terms of the effects of the time variant model on subjective preference. In experiment 1, the delay time of reflection was varied, and in experiment 2, the delay time interval was varied. In both tests, stimuli were presented as a paired, and subjects were asked which sound field was more preferable to listen.

Experiment 1 was performed in order to observe effects of the addition of fluctuation at different delay time. There ware ten stimuli in each motif, (five standards for delay time of the first reflection Δt_1, by two standards that are with and without modulation.). From results of this test, the Δt_1 that showed the maximum scale value of preference with modulation ($[\Delta t_1]_{pm}$) become shorter than that obtained without modulation. From this experiment, the relationship between scale value of preference and Δt_1 was found under the conditions with and without modulation.

Experiment 2 was performed in order to observe the relationship between the scale values of subjective preference and the modulation interval of delay time. In both motifs three of four subjects preferred modulated sound field. From the regression curves, the modulation interval of delay time showing the maximum value of subjective preference is about 0 ms (without modulation) for Motif A, and is about 13 ms for Motif B (with modulation). There is significant difference ($p<0.05$) between sound stimulus 1 (without modulation) and 2 (with modulation) in the case of Motif B. It was suggested that a time-variant sound field might improve subjective preference in the performance of a fast-tempo music which has a short τ_e.

Chapter V describes conclusions and further problems. From the results of the physical examination, it was found that was significant fluctuations of SPL in sound transmission, and the mechanism of fluctuation which was represented by the impulse response with modulated delay time was discussed. From the results of psychological experiments, it was observed that the fluctuation contributed to increase the scale values of subjective preference in a fast-tempo music which has a short τ_e.

Conclusions are summed up as follows.

1) The cumulative distribution of mean squared amplitude that was obtained in the gymnasium fit Nakagami-Rise distribution. The distribution of simulated mean squared amplitude also fit Nakagami-Rise distribution.

2) From the result of the JND of colouration that was caused by the delay time modulation of the first reflection, Δ at JND increased as MF became lower.

3) In the case of Motif A that had long τ_e and was a slow tempo music, Δ at JND was smaller than that obtained in Motif B (a fast tempo music).

4) In the case of the sound field with modulation, it was found that the scale value of subjective preference was increased at the range of short Δt_1.

5) When Motif B that has a short τ_e was selected as sound source, it was found that the most preferred sound field could be obtained when modulation interval was about 13.0 ms.

5.2 Further problems

The fluctuation of SPL which was the specific object in this study was examined about its physical mechanism and its psychological effect on subjective judgment. The air currents caused change in sound transmission and led this fluctuation, but it easyly picked up other factors which caused the change in sound transmission within a room acoustics.

As for the physical aspect, futher problems are how is the effects of other factors (temparature gradients, movement of players and audiences), how is the extension and allowance of them, whether the acoustical model including time variant model would be adopted to other attributs relating to these fluctuation or not.

Concerning the psychological aspect, there are still some uncertainty in the relationship between fluctuation and subjective preference. All the psychological experiments have been conducted using the sine wave as the modulation pattern for the delay time of the first reflection sound. As for the further problems in psychological aspect, the modulation pattern would be examined in order to produce more preferable sound fields. The tests that are relating to brain wave would make the reliable effectiveness of fluctuation.

In the study, we have investigated just a little deeper into the relationship between fluctuation in a room and the subjective judgment for a sound field in room. This study can also be applied to further studies which will expectedly, result in the development of the acoustic design of the fluctuation in a room, open-field construction and electro-acoustic equipment for sound reproduction system.

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APPENDIX A

A.1 Statistical character of amplitude change.

1) Rayleigh distribution

It was said that the fluctuation was caused by the composition of irregular amplitude and phase waves irregularly, which could be expressed by Rayleigh distribution. This distribution is often used in order to describe the fluctuation in the electromagnetic propagation and reverberant sound field. Figure 46 illustrates for the composition of irregular components.

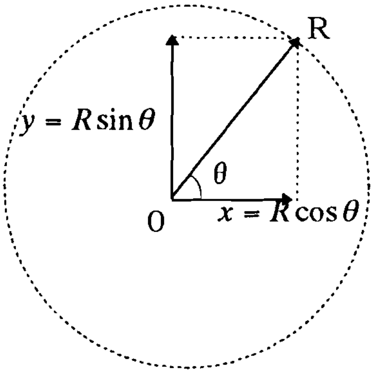

Fig.46 The composition of irregular components.

Amplitude can be expressed by equation (a-1).

$$R(t) = \sum_k a_k \cos(\omega t + \theta_k) \ , \qquad \text{(a-1)}$$

The distribution of amplitude change can be expressed as follows.

$$P(x, y) = \frac{1}{2\pi\sigma^2} e^{-(x^2+y^2)/2\sigma^2} , \qquad \text{(a-2)}$$

substitution $x = R\cos\theta$, $y = R\sin\theta$, and $R = (x^2 + y^2)^{0.5}$ to equation (a-2).

$$p(R) = \frac{R}{2\pi\sigma^2} e^{-R^2/2\sigma^2} \int_0^{2\pi} d\theta = \frac{R}{\sigma^2} e^{-R^2/2\sigma^2}, \qquad \text{(a-3)}$$

Upper examination has been done under the conditions of irregular phase and amplitude change. But Waterhouse proofed that the fluctuation which was caused by the composition of only irregular phase change each other also could be expressed by Rayleigh distribution.

2) Nakagami-Rician distribution (I_0 distribution)

The amplitude fluctuation which was caused by the composition between regular components and the waves that follows upper Rayleigh distribution, could be expressed by Nakagami-Rician distribution [another name, I_0 distribution (zero of bessel function)]. Figure 47 illustrates the composition of regular component and irregular components.

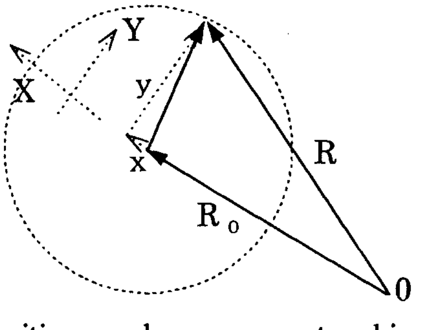

Fig. 47 The composition regular component and irregular component.

$$P(X,Y) = \frac{1}{2\pi\sigma^2} e^{-[(X-R_0)^2+Y^2]/2\sigma^2}, \qquad \text{(a-4)}$$

substitute $R_0 + x = X = R\cos\theta$, $y = Y = R\sin\theta$ to equation (a-4).

$$p(R,\theta) = \frac{R}{2\pi\sigma^2} e^{-[R^2+R_0^2-2RR_0\cos\theta]/2\sigma^2}, \qquad \text{(a-5)}$$

After integration from 0 to 2π in terms of θ, next formula is obtained.

$$P(R) = \frac{R}{2\pi\sigma^2} e^{-[R^2+R_0^2]/2\sigma^2} \int_0^{2\pi} e^{RR_0 \cos\theta/\sigma^2} d\theta, \qquad \text{(a-6)}$$

then $$\int_0^{2\pi} e^{RR_0 \cos\theta/\sigma^2} d\theta = 2\pi I_0\left(\frac{RR_0}{\sigma^2}\right), \qquad \text{(a-7)}$$

$$P(R) = \frac{R}{\sigma^2} e^{-[R^2+R_0^2]/2\sigma^2} I_0\left(\frac{RR_0}{\sigma^2}\right), \qquad \text{(a-8)}$$

Nakagami-Rician distribution might have the connection to m-distribution and Gamma distribution as shown below.

$$I_0(x) = \sum_{k=0}^{\infty} \frac{(-1)^k (x/2)^{2k}}{k!\Gamma(k+1)}, \qquad \text{(a-9)}$$

when $RR_0 >> \sigma^2$, equation (a-5) can be expressed by equation (a-6).

$$P(R) \approx \frac{1}{\sigma\sqrt{2\pi}} e^{-(R+R_0)^2/2\sigma^2}, \qquad \text{(a-10)}$$

3) m-distribution

M-distribution includes Rayleigh distribution and Normal distribution in a particular case, and has the similar characteristic to Nakagami-Rician distribution.

$$P(R) = \frac{2m^m R^{2m-1}}{\Gamma(m)(\overline{R^2})^m} e^{-m(R^2/\overline{R^2})}, \qquad \text{(a-11)}$$

When $m = 1$, m-distribution corresponds to Rayleigh distribution. It was said that the parameter m represents the degree of fluctuation. The distribution of mean squared amplitude, that was Gamma distribution, could be substituted by $R^2 = W$ and $m = \nu$ into equation (a-12).

$$P(W) = \frac{\gamma^{m} W^{\upsilon-1}}{\Gamma(\upsilon)} e^{-\gamma W}, \qquad \text{(a-12)}$$

It was also said that this distribution corresponded to Rayleigh distribution when $\nu = 1$, and was approximately equals to Nakagami-Rician distribution when $\nu > 1$.

APPENDIX B

JND of colouration by using Oct-band noise.

In chapter III, sine wave was used as the modulation pattern of the delay time. However from the fluctuation SPL analysis in chapter II, it was thought that the modulation pattern of delay time was 1/1 Oct-band wave. So JND of colouration obtained by using Oct-band wave as modulation pattern was performed, and its results are shown below. The analysis of τ_e was different from the way performed in chapter III, so the results were described in this Appendix B.

1) The method of experiment.

As for the experimental conditions, sound source, time structure of sound stimulus, the experimental method and Δt_1 were as the same as that in chapter III. Four standards of modulation frequency, 0.1-, 0.5-, 1.0- and 2.0-Hz were selected. 1/1 Oct-band noise at low frequencies was generated by the software we made for this experiment. Figure 48 shows the block diagram of experimental set-up. Each modulation pattern was recorded in DAT and was input into the delay machine. Figure 49 shows time feature and its spectrum of modulation pattern.

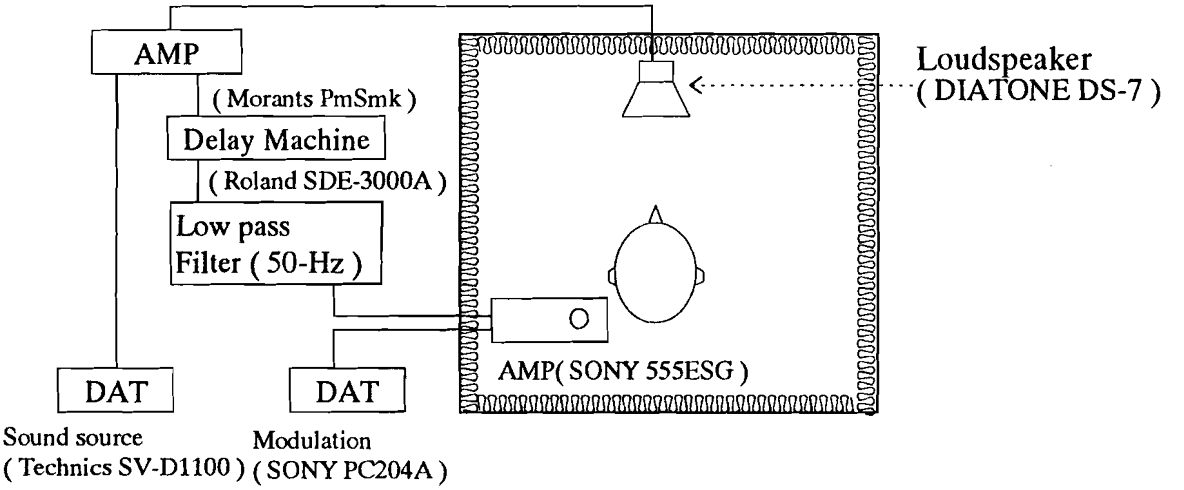

Fig. 48 Block diagram experiment al set-up.

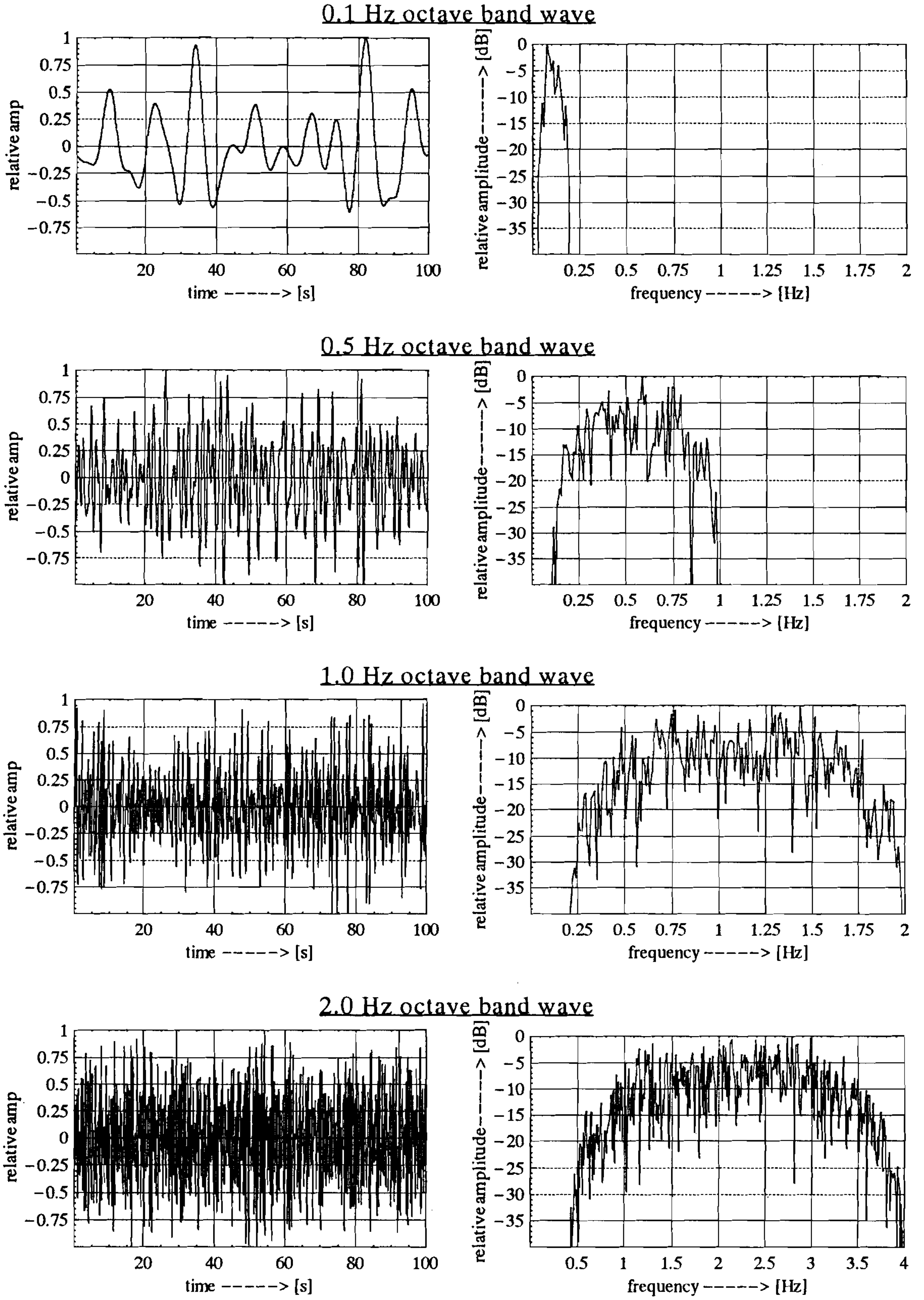

Fig. 49 The modulation patterns and its spectrums. (Left row shows the modulation pattern in time, and right row shows the spectrum of the modulation pattern.)

2) Results and discussions

Figure 50 shows the results of this experiment compared to the results of chapter Ⅲ. As the modulation frequency increases, ⊿ at JND decreases. ⊿ at JND using octave band noise are bigger than that using sine wave at any modulation frequencies. ⊿ at JND using Motif A, slower tempo music, are smaller than that using Motif B, in the similar relationship obtained in chapter Ⅲ. It meant that colouration in the case of Motif A was easier to discern than that of Motif B. $⊿_{oct}$ / $⊿_{sin}$ of Motif B is relatively bigger than that of Motif A.

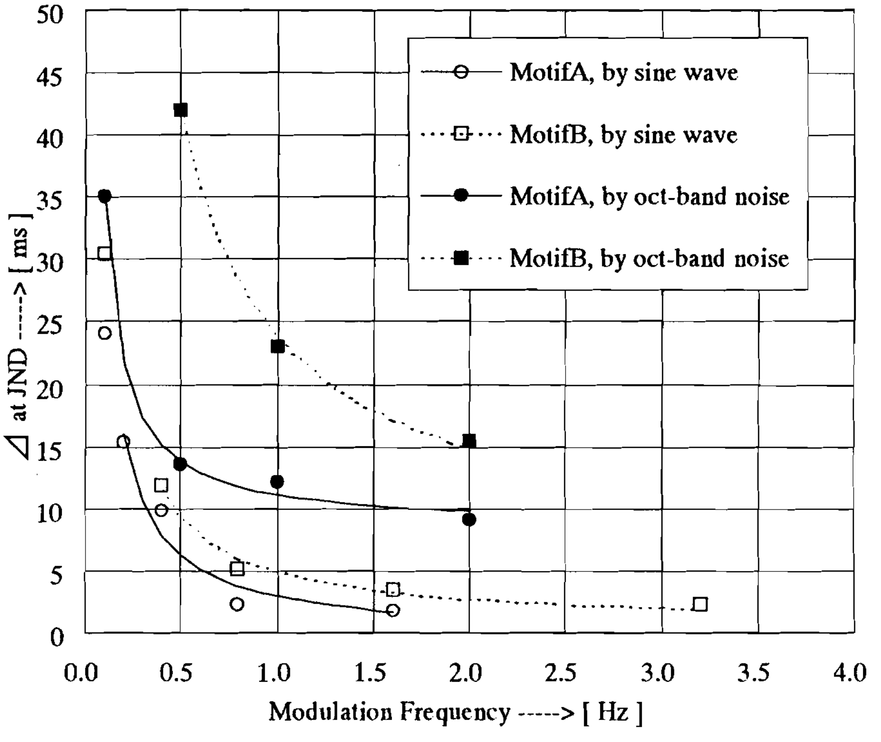

Fig. 50 The relationship between modulation frequencies and ⊿ at JND.
(○: Motif A using sine wave as the modulation pattern, □: Motif B using sine wave, ●: Motif A using Oct-band noise, ■: Motif B using Oct-band noise.)

3) τ_e of sound field.

Figure 51 shows the relationship between τ_e values of sound fields with and without ⊿. The solid line indicates τ_e of sound field without ⊿, and a dotted line shows the minimum τ_e with ⊿ (JND). The maximum difference of τ_e values of sound field between with and without ⊿, which may be regarded as a cue of JND was about 190ms. The maximum difference are bigger than that obtained by sine wave as modulation pattern in chapter III.

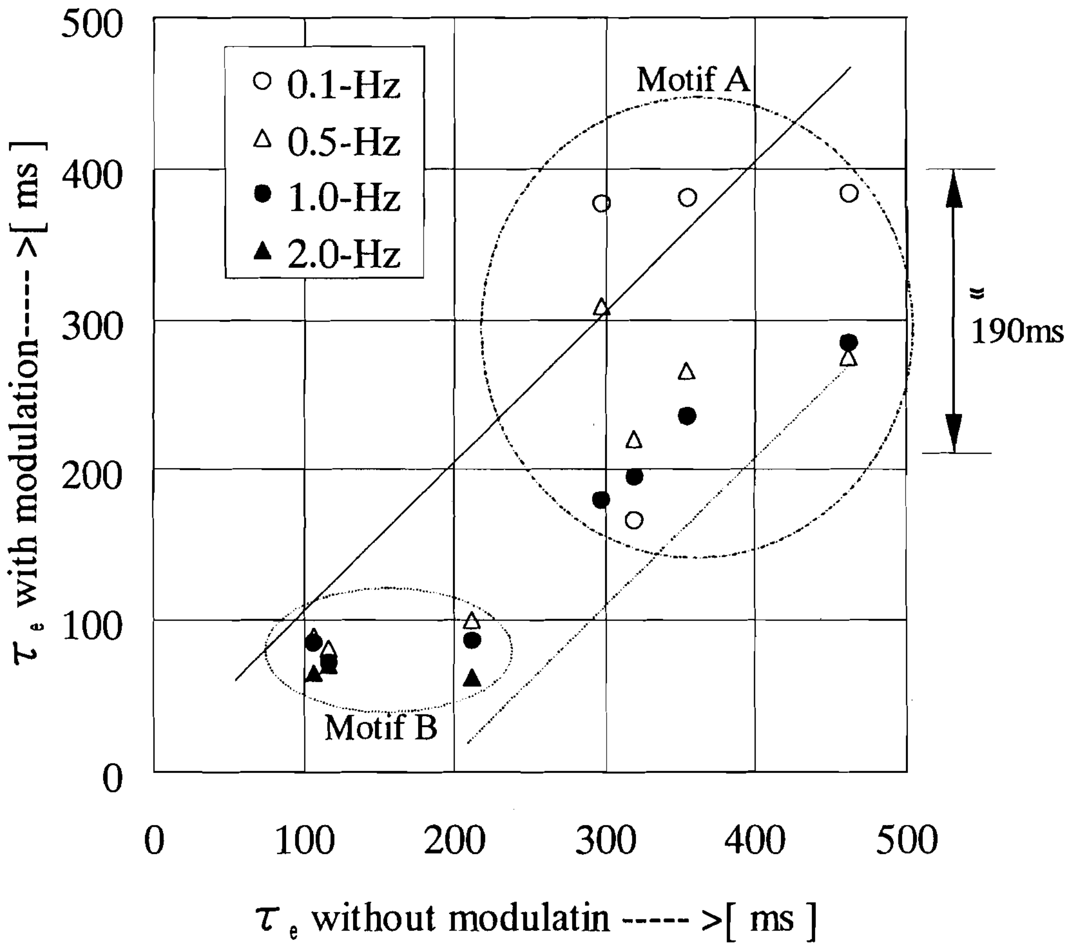

Fig. 42 The relationship between τ_e of sound field with and without ⊿ (JND).
(○: represents 0.1-Hz Oct-band wave, △: 0.5-Hz, ●: 1.0-Hz, ▲: 2.0-Hz)

4) Conclusions

$\varDelta_{Oct}$ is bigger than $\varDelta_{sin}$. It means that the desertion of colouration by Oct-band noise modulation is difficult rather than that by sin wave modulation. And $\varDelta$ of Motif A is smaller than that of Motif B. These tendencies are similar to the result of chapter Ⅲ. The result would be referred in the next experiment of subjective preference.

APPENDIX C

The running τ_e of sound source

It was supposed that τ_e of the sound field might be a cue as for the subjective judgment in the temporal domain. And τ_e is the important parameter to design sound field and determines Δt_1 which was the most preferable delay time of the first reflection.

Accordingly, authors have searched for the standard condition to calculate τ_e values. And it necessary to make the τ_e value of sound sources (Motif A and B) clear at the stage of the psychological experiment. The problem of the τ_e calculation depends on time interval in order to get the inclination curve. It is not avoidable to calculate τ_e value. The running τ_e of the direct sound in an anechoic room of Hazama Corp., Ibaraki was examined by varying the calculation condition.

1) The measurement condition.

Figure 52 shows the measurement condition. The sound source was measured by the audio system that was used for the psychological experiments, and through A-weighted filter. The height of the microphone was set as the same as that of the subjects' ears.

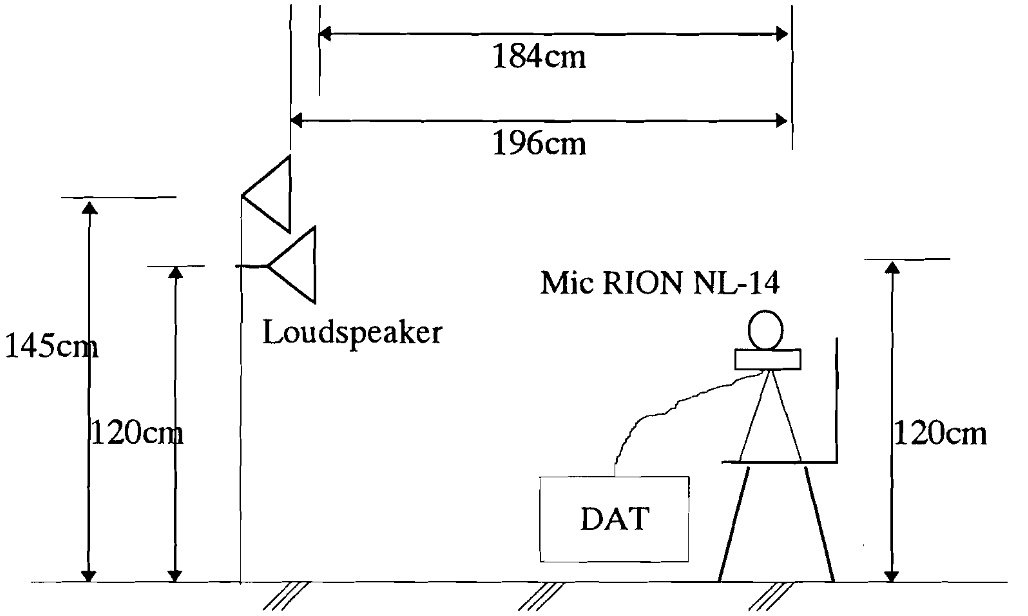

Fig. 52 The measurement condition.

2) Results

a) Condition of analysis.

Table 23 shows the condition of the τ_e analysis. The analysis was performed by ASA-2, the hardware and software to calculate running τ_e. In the case of Motif A, 4 types of time window interval were selected in order to calculate the inclination curve of ACF.

Table. 23 The calculation condition of running τ_e analysis.

Parameter item	Motif A	Motif B
Time interval to calculate autocorrelation function. [ms]	2000	2000
Time interval to calculate the inclination of auto-correlation function. [ms]	50, 75, 100 and 125	40
Running interval [ms]	100	100

b) The result of τ_e analysis.

Figure 53 and 54 show the running τ_e of each Motif and its wave form. Table 24 and 25 shows lists of fundamental statistical data for running τ_e data. Because of the running τ_e values of front part in Motif A is different from rear part. So sound source were divided into two different sections, first for 8 seconds, and first for 6 seconds.

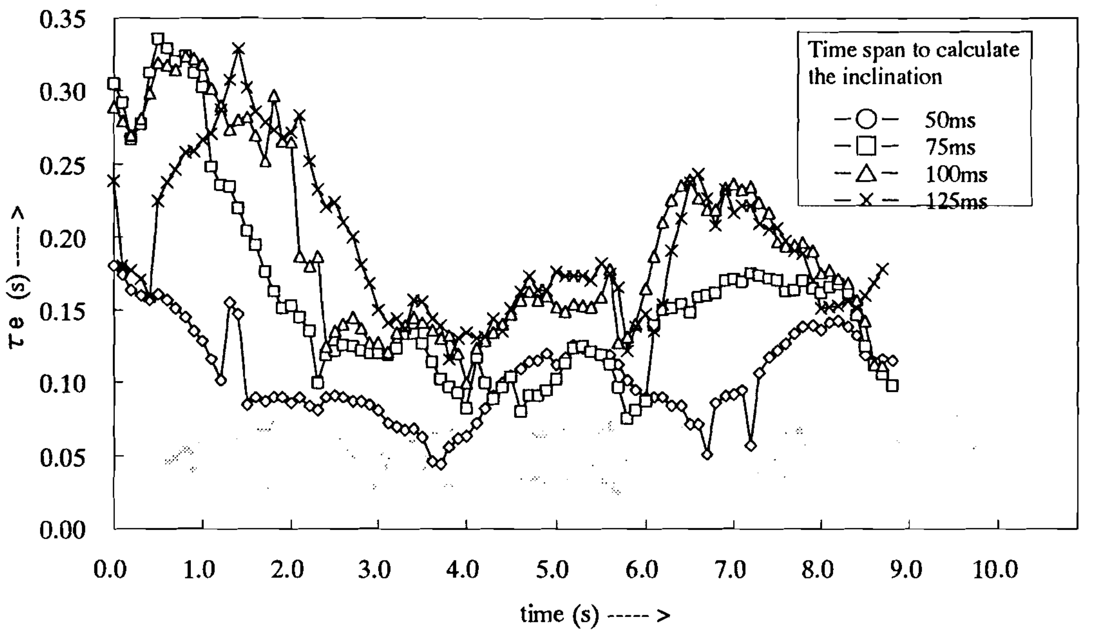

Fig. 53 Running τ_e of sound source (Motif A).

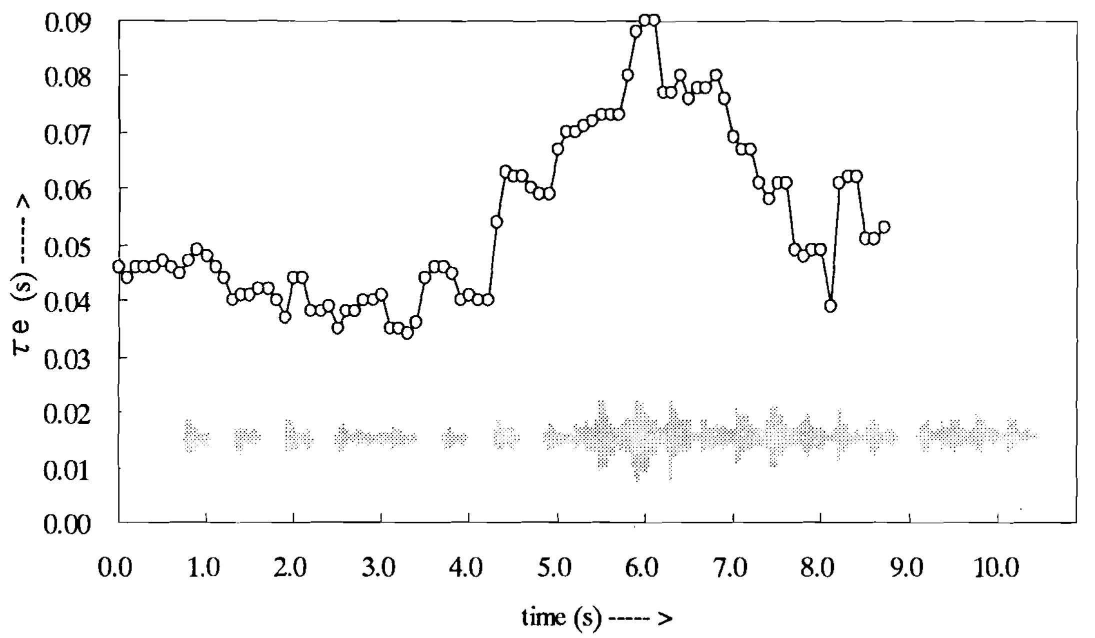

Fig. 54 Running τ_e of sound source (Motif B).

Table.24 Lists of fundamental running τ_e data for each Motif. (Unit: ms, the length of sound source was first 8.9 seconds.)

	Motif A				Motif B
Time interval for inclination [ms]	50	75	100	125	40
Maximum τ_e	180.0	335.0	324.0	329.0	90.0
Minimum τ_e	44.0	75.0	99.0	116.0	34.0
Averaged τ_e	105.0	157.6	195.2	194.2	54.3
Standard deviation	31.0	67.0	63.9	50.4	15.1

Table. 25 List of fundamental running τ_e data for each Motif. (Unit: ms, the length of sound source was first 6.0 seconds.)

	Motif A				Motif B
Time interval for inclination [ms]	50	75	100	125	40
Maximum τ_e	180.0	335.0	324.0	329.0	90.0
Minimum τ_e	44.0	75.0	99.0	116.0	34.0
Averaged τ_e	104.2	159.2	194.3	195.9	49.9
Standard deviation	32.9	79.9	73.1	57.0	14.0

3) Conclusions.

τ_e values of Motif A depended on the time window interval in terms of calculation of the inclination curve. More than 75 ms, the maximum data was constant, but the minimum data were different. As the time interval to calculate the inclination becomes shorter, the minimum data becomes smaller. Data obtained by 50 ms as the time window showed the smallest value than any other data. From observation of analysis, at the case of more than 75 ms, τ_e showed the stability. So, 75 ms would be selected as the time window to calculate the degree of inclination curve for Motif A. The degree of inclination for Motif B had the same tendency of Motif A. 50 ms would be selected the time window to calculate the degree of inclination curve for Motif B.