Evaluation of broad-band noise mixed with amplitude-modulated sounds

Sonoko Kuwano,* Seiichiro Namba,* Kenji Kurakata,**
and Yoshimasa Kikuchi***

**College of General Education, Osaka University,*

1-1 Machikaneyama, Toyonaka, 560 Japan

***Faculty of Human Sciences, Osaka University,*

1-2 Yamadaoka, Suita, 565 Japan

****Daikin Industries Ltd.,*

1304 Kanaoka-cho, Sakai, 591 Japan

(Received 29 September 1993)

A series of experiments was conducted concerning the effect of amplitude-modulated (AM) sounds on the impression of broad-band noise. The following results were found: (1) AM sounds in broad-band noise were detected when S/N was around zero (S : the level of AM sound, N : $1/3$ octave band level of broad-band noise with center frequency corresponding to the carrier frequency of AM sounds). Close examination showed that carrier frequency, modulation frequency and modulation depth had a systematic effect on the detection of AM sounds. (2) The loudness of broad-band noise mixed with AM sounds could be approximately evaluated by loudness level based on ISO 532B (LL_z). (3) The timbre of broad-band noise mixed with AM sounds was judged to be more metallic as the carrier frequency of AM sounds became higher and to be more clamorous as the carrier frequency became lower. This suggests that the timbre is deteriorated when AM sounds are mixed with broad-band noise. The three factors were extracted by the factor analysis: they were "metallic" or "unpleasant," "powerful" and "rough."

Keywords: Loudness, Timbre, Air-conditioner noise, Amplitude-modulated sound

PACS number: 43. 66. -x, 43. 50. -x

1. INTRODUCTION

In order to create comfortable sound environment, it would be desirable to eliminate uncomfortable sounds and find the factors which contribute in designing comfortable sounds environment. A great effort has been focused on decreasing sound levels of various machine noises. Actually the power levels of aircrafts or cars have decreased remarkably. However, it sometimes happens that when the sound level of a given noise source decreased, another uncomfortable sound which was masked by that sound became audible. Furthermore, complete quietness without any audible sounds is not always comfort-

able as people may feel when they enter into an anechoic chamber for the first time. It would be more agreeable to have some sounds which are not disturbing.

Then, what sounds are appropriate as background sounds in our living environment? The conditions which are desired for such background sounds may be that they are not disturbing, easy to be habituated to, and not unnatural in the environment. Air-conditioner noise can be one of such sounds. To fulfil the above conditions air-conditioner noise is desired to be soft and have a good sound quality. If the sound contains a specific component, even though the sound level is low, it may be perceived as

being disturbing or noisy. In our previous study¹⁾ the effect of frequency-modulated (FM) sounds on the impression of air-conditioner noise was investigated and the results suggested the followings:

(1) FM sounds mixed with broad-band noise can be just detectable when S/N is around zero (S : the level of FM sound, N : the 1/3 octave band level of broad-band noise with center frequency corresponding to the carrier frequency of FM sounds).

(2) FM sounds mixed with broad-band noise can be detected at S/N of -10 dB or less when it is interrupted.

(3) The loudness of broad-band noise shows good correspondence with L_{Aeq} (equivalent continuous A-weighted sound pressure level; L_{Aeq} will be abbreviated as L_{eq} in this paper). However, when a prominent frequency component is included, loudness level based on ISO 532B²⁾ (abbreviated as LLz) shows better correspondence than L_{eq} .

(4) The timbre becomes deteriorated when the level of specific frequency component increases or when its frequency becomes high. The effects of specific frequency components on timbre were found even when the overall values of L_{eq} were kept constant. Neither L_{eq} nor LLz is sufficient for evaluating these effects. The calculated sharpness proposed by von Bismarck³⁾ was found to be an appropriate method for evaluating the metallic impression of timbre.

In the present study the effect of amplitude-modulated (AM) sounds on the impression of simulated air-conditioner noise will be examined, since air-conditioner noise sometimes contains periodical level fluctuations such as AM which will easily draw our attention and make the sound quality deteriorated.⁴⁾

2. EXPERIMENT 1

In Experiment 1, just detectable level of amplitude-modulated (AM) sounds when they were mixed with broad-band noise was examined using the method of limits.

2.1 Stimuli

AM sounds: Forty-four kinds of amplitude-modulated sound were used. Their carrier frequency, modulation frequency and modulation depth are shown in Table 1. These stimulus conditions were selected taking the deteriorating factors of actual air-conditioner noise into account.⁴⁾ In

Table 1 Stimuli used in Experiment 1.

No.	CF (Hz)	MF (Hz)	MD (%)	No.	CF (Hz)	MF (Hz)	MD (%)
1	125	—	0	23	500	—	0
2	125	1	50	24	500	1	50
3	125	1	100	25	500	1	100
4	125	2	50	26	500	2	50
5	125	2	100	27	500	2	100
6	125	4	50	28	500	4	50
7	125	4	100	29	500	4	100
8	125	8	50	30	500	8	50
9	125	8	100	31	500	8	100
10	125	16	50	32	500	16	50
11	125	16	100	33	500	16	100
12	250	—	0	34	1,000	—	0
13	250	1	50	35	1,000	1	50
14	250	1	100	36	1,000	1	100
15	250	2	50	37	1,000	2	50
16	250	2	100	38	1,000	2	100
17	250	4	50	39	1,000	4	50
18	250	4	100	40	1,000	4	100
19	250	8	50	41	1,000	8	50
20	250	8	100	42	1,000	8	100
21	250	16	50	43	1,000	16	50
22	250	16	100	44	1,000	16	100

CF: carrier frequency, MF: modulation frequency, MD: modulation depth.

Fig. 1 Frequency characteristics of broad-band noise which simulated air-conditioner noise.

this study amplitude-modulated sounds with modulation depth 0% (pure tone) were used as reference stimuli. Carrier tones were generated with a function synthesizer (NF-DF191) and their amplitude was modulated with a programmable attenuator controller (AD system) and a personal computer (NEC PC9801-RX).

Broad-band noise: The frequency characteristics of pink noise was modified with a digital filter (MTT DSP5200AL/24) so that it simulated that of an actual air-conditioner noise when the noise was presented through headphones in a sound-proof

room. The frequency characteristics of the noise is shown in Fig. 1.

2.2 Procedure

The just detectable level of AM sounds mixed with broad-band noise was measured using the method of limits. The broad-band noise was continuously presented at the level of 40 dBA. AM sounds was also presented continuously, the level of which was increased in ascending series or decreased in descending series by 1 dB step every 2 s. Subjects were instructed to keep pressing a key on a response box while the AM sounds were audible to them. Each subject conducted four ascending series and four descending series after training.

2.3 Apparatus

The stimuli were reproduced with two DAT recorders, one for AM sounds (Victor XD-X1100) and the other for broad-band noise (Sony 55ES), and presented to subjects through a mixer (Sony MX-710) and headphones (STAX SRD-X pro.) in a sound proof room.

2.4 Subjects

One male and four female subjects aged between 26 and 44 with normal hearing ability participated in Experiment 1.

2.5 Results

Since one-third octave band width is similar to the critical band width above about 250 Hz and used for calculating loudness level standardized in ISO532B,²⁾ the mean energy level of 1/3 octave band with center frequency of each carrier frequency was calculated for the AM sounds (*S*: signal) and the broad-band noise (*N*: background). The just detectable levels of AM sounds are shown with the corresponding 1/3 octave band level of the broad-band noise in Table 2. The difference in 1/3 octave band level between AM sounds when they were just detected and broad-band noise (*S/N*) is plotted against modulation frequency in Figs. 2 and 3. The following results were suggested:

(1) AM sounds in broad-band noise were detected when *S/N* was around zero.

(2) The just detectable level was lower for AM sounds than for pure tones except for modulation frequency of 16 Hz. This suggests that level-

Table 2 Just detected level of amplitude-modulated sounds in broad-band noise.

CF		125 Hz		250 Hz		500 Hz		1 kHz	
MF (Hz)	MD (%)	<i>A</i> (dB)	<i>C</i> (dB)	<i>A</i> (dB)	<i>C</i> (dB)	<i>A</i> (dB)	<i>C</i> (dB)	<i>A</i> (dB)	<i>C</i> (dB)
—	0	43.5	6.2	33.4	1.0	31.0	−2.5	27.3	−2.6
1	50	41.0	3.7	31.7	−0.7	29.9	−3.6	25.3	−4.6
	100	39.9	2.6	30.1	−2.3	28.7	−4.8	23.9	−6.0
2	50	41.2	3.9	31.9	−0.5	30.6	−2.9	24.9	−5.0
	100	39.9	2.6	30.4	−2.0	29.6	−3.9	23.4	−6.5
4	50	42.8	5.5	32.0	−0.4	30.0	−3.5	26.0	−3.9
	100	41.4	4.1	31.2	−1.2	29.8	−3.7	24.3	−5.6
8	50	42.1	4.8	33.1	0.7	30.5	−3.0	26.5	−3.4
	100	43.0	5.7	33.7	1.3	30.6	−2.9	26.1	−3.8
16	50	43.3	6.0	33.9	1.5	31.6	−1.9	27.7	−2.2
	100	43.1	5.8	35.1	2.7	32.3	−1.2	26.6	−3.3
Noise (B)		37.3		32.4		33.5		29.9	

CF: carrier frequency, MF: modulation frequency, MD: modulation depth.

A: The mean energy level of AM sounds which were just detected.

B: The mean energy level of 1/3 octave band of broad-band noise with center frequency corresponding to the carrier frequency of AM sounds.

C: $A - B$ (dB)

Fig. 2 Just detected level of AM sounds in broad-band noise when modulation depth was 50%. (*S*: the level of AM sounds, *N*: 1/3 octave band level of broad-band noise with center frequency corresponding to the carrier frequency of AM sounds.)

Fig. 3 Just detected level of AM sounds in broad-band noise when modulation depth was 100%.

fluctuating sounds can easily be detected.

(3) The just detectable level of AM sounds decreased as the carrier frequency became higher.

(4) The just detectable level became minimum when the modulation frequency was 1 or 2 Hz in the range of modulation frequency used in this experiment. The just detectable level increased as the modulation frequency became higher.

(5) The effect of modulation depth varied depending on the modulation frequency. When the modulation frequency was low, the larger modula-

tion depth produced lower just detectable level. There was little effect of modulation depth when modulation frequency was higher.

3. EXPERIMENT 2

The overall loudness of broad-band noise mixed with AM sounds was examined in Experiment 2.

3.1 Stimuli

Taking the results of Experiment 1 into account, 20 kinds of AM sound were used as stimuli in Experiment 2. They are listed in Table 3. The level of broad-band noise was kept constant at 40 dBA. The broad-band noise was electrically mixed with AM sounds. The just detectable level of AM sounds obtained in Experiment 1 was regarded as $S/N=0$ (*S*: the level of AM sounds, *N*: the level of broad-band noise) and five kinds of S/N were used; 0, 5, 10, 15 and 20 dB. Broad-band noise of four levels, 40, 45, 50 and 55 dBA, were also added in the stimulus series. Therefore, the stimulus series consisted of 104 kinds of stimulus. The duration of each stimulus was 3 s.

3.2 Procedure

Magnitude estimation was used. 104 stimuli were presented to subjects in random order with 5 s silent intervals. The subjects were instructed to judge the overall loudness of each sound by assigning any positive number which they thought reflected the impression of loudness. No modulus was used. A training was given to subjects using six stimuli among 104 stimuli used in the experiment. Two trials were conducted after training.

3.3 Apparatus

The stimuli were reproduced with a DAT recorder (Victor XD-Z1100) and presented to subjects' ears through headphones (STAX SRD-X pro.) in a sound proof room.

3.4 Subjects

Eight male and twelve female subjects aged between 21 and 45 (average age was 26.3) with normal hearing ability participated in Experiment 2.

3.5 Results

The statistically significant coefficient of correlation was found between two trials for every subject as shown in Table 4, which confirms the reliability

Table 3 Stimuli used in Experiment 2.

No.	CF (Hz)	MF (Hz)	MD (%)	SN dB	No.	CF (Hz)	MF (Hz)	MD (%)	SN dB
1	125	—	0	0	51	500	—	0	0
2	125	—	0	5	52	500	—	0	5
3	125	—	0	10	53	500	—	0	10
4	125	—	0	15	54	500	—	0	15
5	125	—	0	20	55	500	—	0	20
6	125	4	50	0	56	500	4	50	0
7	125	4	50	5	57	500	4	50	5
8	125	4	50	10	58	500	4	50	10
9	125	4	50	15	59	500	4	50	15
10	125	4	50	20	60	500	4	50	20
11	125	4	100	0	61	500	4	100	0
12	125	4	100	5	62	500	4	100	5
13	125	4	100	10	63	500	4	100	10
14	125	4	100	15	64	500	4	100	15
15	125	4	100	20	65	500	4	100	20
16	125	16	50	0	66	500	16	50	0
17	125	16	50	5	67	500	16	50	5
18	125	16	50	10	68	500	16	50	10
19	125	16	50	15	69	500	16	50	15
20	125	16	50	20	70	500	16	50	20
21	125	16	100	0	71	500	16	100	0
22	125	16	100	5	72	500	16	100	5
23	125	16	100	10	73	500	16	100	10
24	125	16	100	15	74	500	16	100	15
25	125	16	100	20	75	500	16	100	20
26	250	—	0	0	76	1,000	—	0	0
27	250	—	0	5	77	1,000	—	0	5
28	250	—	0	10	78	1,000	—	0	10
29	250	—	0	15	79	1,000	—	0	15
30	250	—	0	20	80	1,000	—	0	20
31	250	4	50	0	81	1,000	4	50	0
32	250	4	50	5	82	1,000	4	50	5
33	250	4	50	10	83	1,000	4	50	10
34	250	4	50	15	84	1,000	4	50	15
35	250	4	50	20	85	1,000	4	50	20
36	250	4	100	0	86	1,000	4	100	0
37	250	4	100	5	87	1,000	4	100	5
38	250	4	100	10	88	1,000	4	100	10
39	250	4	100	15	89	1,000	4	100	15
40	250	4	100	20	90	1,000	4	100	20
41	250	16	50	0	91	1,000	16	50	0
42	250	16	50	5	92	1,000	16	50	5
43	250	16	50	10	93	1,000	16	50	10
44	250	16	50	15	94	1,000	16	50	15
45	250	16	50	20	95	1,000	16	50	20
46	250	16	100	0	96	1,000	16	100	0
47	250	16	100	5	97	1,000	16	100	5
48	250	16	100	10	98	1,000	16	100	10
49	250	16	100	15	99	1,000	16	100	15
50	250	16	100	20	100	1,000	16	100	20
					101	noise	40 dB		
					102	noise	45 dB		
					103	noise	50 dB		
					104	noise	55 dB		

CF: carrier frequency, MF: modulation frequency, MD: modulation depth.

Table 4 Coefficient of correlation between two trials of each subject.

Subject	<i>r</i>
1	0.618
2	0.632
3	0.659
4	0.612
5	0.357
6	0.512
7	0.372
8	0.835
9	0.813
10	0.649
11	0.229
12	0.507
13	0.268
14	0.811
15	0.474
16	0.792
17	0.425
18	0.551
19	0.387
20	0.433
Mean	0.930

Fig. 4 Relation between loudness judged using magnitude estimation and *LLz* for broad-band noise mixed with AM sounds whose carrier frequency was 125 Hz. High correlation can be seen between them. This power function was used as a reference function for calculating the point of subjective equality (*PSE*).

of the judgments. The coefficient of correlation between geometric means of judgments by 20 subjects for two trials was 0.930. Therefore, the geometric means of 40 judgments by twenty subjects were calculated and used for further analyses.

LLz of each stimulus was calculated according to ISO 532B^{2,5)} on the basis of the mean energy level

Fig. 5 Relation between loudness expressed with *PSE* and *LLz*. High correlation and small RMS suggest that *LLz* is a good measure for evaluating the loudness of broad-band noise mixed with AM sounds. ● 125 Hz, ○ 250 Hz, ▲ 500 Hz, △ 1 kHz, × Noise only.

of 1/3 octave band.⁶⁾ The relation between loudness judgment and *LLz* for 25 kinds of noise mixed with AM sounds whose carrier frequency is 125 Hz is shown in Fig. 4. The carrier frequency of 125 Hz was selected since the dynamic range of *LLz* was the widest among the broad-band noise mixed with AM sounds used. A high correlation can be seen between them and the exponent of power function was 0.28. Using this power function as a reference function, the values of *LLz* corresponding to loudness judgment to each stimulus were calculated and these values were regarded as *PSE* (point of subjective equality). The relation between *PSE* and *LLz* is shown in Fig. 5. A high coefficient of correlation can be seen between them ($r=0.944$) and the deviation from the unit line is small ($RMS=1.01$ dB). This suggests that the loudness of these sounds can be approximately evaluated by *LLz*.

Close examination shows that broad-band noise without AM sounds was judged to be louder than broad-band noise mixed with AM sounds. This may be related to the phenomenon that the overall loudness of broad-band noise mixed with a pure tone component is perceived as being softer as S/N (S : the level of pure tone; N : the level of broad-band noise) increases.⁷⁾ Hellman and Zwicker⁸⁾ ex-

Fig. 6 The difference between *PSE* and *LLz* is plotted against modulation frequency of AM sounds. The carrier frequency of AM sounds were 125 Hz in Fig. 6 (a), 250 Hz in Fig. 6 (b), 500 Hz in Fig. 6 (c) and 1 kHz in Fig. 6 (d). $\square$ $SN=0$ dB, $\blacklozenge$ $SN=5$ dB, $\times$ $SN=10$ dB, $\diamond$ $SN=15$ dB, $\blacksquare$ $SN=20$ dB.

plained that this might be due to the decrease of the area of excitation pattern, which occurred when S/N increased keeping the overall sound pressure level constant. This is an interesting phenomenon which

requires future investigation.

In order to examine the effects of carrier frequency, modulation frequency, modulation depth and S/N , the difference between *PSE* and *LLz* is

Fig. 7 Relation between PSE and L_{eq} . It was found that L_{eq} was not always a good measure of loudness of sounds which had prominent frequency components. ● 125 Hz, ○ 250 Hz, ▲ 500 Hz, △ 1 kHz, × Noise only.

plotted against modulation frequency in Figs. 6 (a)–(d). It was suggested from these figures that any of these factors had little systematic effect on the loudness of these sounds.

The relation between L_{eq} and PSE is shown in Fig. 7. L_{eq} showed lower correlation with PSE than LLz . Especially when S/N was larger and the carrier frequency was higher, the deviation of PSE from L_{eq} became larger. This suggests that L_{eq} is not suitable to evaluate the sounds with prominent frequency components as the stimuli used in this experiment.

4. EXPERIMENT 3

In Experiment 2 the broad-band noise mixed with AM sounds were found to be judged softer than the broad-band noise without AM sounds though both sounds had the same energy. However, since it is probable that the overlapping of AM sounds may deteriorate the impression of timbre, in Experiment 3 the timbre of broad-band noise mixed with AM sounds was examined using semantic differential.

4.1 Stimuli

The same stimuli used in Experiment 2 were used in Experiment 3 except that only one level of broad-band noise, 40 dBA, was used. In total 101 stimuli

were used in Experiment 3. The L_{eq} values of all these stimuli were fixed at 40 dBA and the duration was 3 s.

4.2 Procedure

The timbre of these stimuli was examined using semantic differential. Each stimulus was presented twice with 3 s silent intervals. The subjects were instructed to judge the timbre of each stimulus using 12 pairs of adjective¹⁾ shown in Fig. 8. Three different orders of adjective pairs were prepared. Subjects conducted the experiment after training.

4.3 Apparatus

The same equipment was used as in Experiment 2.

4.4 Subjects

The same 20 subjects as in Experiment 2 participated in Experiment 3, but in different days.

4.5 Results

The judgments by 20 subjects were averaged and examples of the profiles are shown in Figs. 8–10. The impressions “clamorous,” “impure” and “dull” became stronger as the carrier frequency became

Fig. 8 An example of semantic profiles. (Effect of carrier frequency)

lower. On the other hand, the impressions "metallic" and "shrill" became stronger as the carrier frequency became higher. This fact suggests that both low and high frequency components produced negative impressions.

In higher carrier frequency the impressions "hard," "distinct," "shrill," "metallic," "discordant" and "unpleasant" became stronger as S/N increased.

There was little systematic effect of modulation frequency or modulation depth on the impression of these sounds.

The result of factor analysis is shown in Table 5. The three factors were extracted. Factor 1 showed high loadings on the adjective scales "gentle-hard," "calm-shrill," "deep-metallic," "harmonious-discordant," "smooth-harsh" and "pleasant-unpleasant." Factor 1 can be regarded as "metallic"

Fig. 9 An example of semantic profiles.
(Effect of carrier frequency)

Fig. 10 An example of semantic profiles.
(Effect of S/N)

Table 5 Results of factor analysis.

	I	II	III
loud — soft	0.027	0.688	0.082
gentle — hard	0.738	-0.102	-0.071
pure — impure	-0.074	0.008	0.663
clamorous — quiet	-0.055	0.662	-0.215
calm — shrill	0.774	0.115	-0.012
distinct — dull	-0.373	0.276	0.504
deep — metallic	0.706	0.060	-0.277
harmonious — discordant	0.807	0.030	0.137
smooth — harsh	0.662	0.046	-0.062
pleasant — unpleasant	0.681	-0.128	0.287
powerful — weak	0.067	0.680	0.064
flat — rumbling	0.340	-0.193	0.577

or "unpleasant" factor. Factor 2 showed high loadings on the adjective scales "loud-soft," "clamorous-quiet" and "powerful-weak." Factor 2 can be regarded as "powerful" factor. Factor 3 showed high loadings on the adjective scales "pure-impure," "distinct-vague" and "flat-rumbling." Factor 3 can be regarded as "rough" factor. These three factors were stably found even when factor analysis was conducted in each carrier frequency or each S/N .

5. DISCUSSION

5.1 Detection of AM Sounds

AM sounds in broad-band noise were just detected when the mean energy level of AM sounds was approximately equal to the 1/3 octave band mean energy level of broad-band noise with center frequency corresponding to the carrier frequency of AM sounds. This results agree with the previous findings on masking⁹⁾ and critical band.¹⁰⁾ Close examination shows interesting and systematic effects of carrier frequency, modulation frequency and modulation depth on the detection of AM sounds.

The just detectable level was lower for AM sounds than for pure tones except for modulation frequency of 16 Hz. This suggests that level-fluctuating sounds can easily be detected. This is the similar findings to our previous study with FM sounds¹⁾ when they were interrupted. As pointed out in profile analysis¹¹⁾ subjects may detect the spectral change of the sounds when amplitude of the specific frequency components of the sounds varied.

The just detectable level became minimum when the modulation frequency was 1 or 2 Hz and it increased as the modulation frequency became higher. This may be related to the impression of fluctuation strength. When the amplitude of a sound is modulated at low frequencies up to about 20 Hz, the sensation of fluctuation strength is elicited and it becomes maximum at the modulation frequency of about 4 Hz.^{12,13)} Also the just-noticeable degree of amplitude modulation becomes low in the modulation-frequency between 2 and 5 Hz.¹³⁾ The modulation frequency where the just detected level was minimum in this experiment seems to correspond to the modulation frequency which produces the maximum fluctuation strength or the minimum just-noticeable degree of amplitude modulation. This may suggest that our hearing system is possibly sensitive to the amplitude modulation around this

modulation frequency.

The just detectable level of AM sounds decreased as the carrier frequency became higher. This may partly be due to the difference in sensitivity to the frequencies. There were some differences in sensation levels among the 1/3 octave band levels of the broad-band noise.

The effect of modulation depth varied depending on the modulation frequency. When the modulation frequency was low, *i.e.* when AM sounds were more easily detected, the larger modulation depth produced lower just detectable level. This result is similar to the previous findings on fluctuation strength^{12,13)} which increased as modulation depth increased. There was little effect of modulation depth when modulation frequency was higher.

5.2 Loudness

L_{eq} is usually shows good correspondence with the loudness of various sounds.¹⁴⁾ However, when prominent frequency components are included in the sounds, frequency correction with A-weighting is not always sufficient.⁶⁾ More precise method is needed. The loudness level standardized in ISO 532B³⁾ (LLz) is based on the psychoacoustical findings of masking, critical band, *etc.* and can be a good method for evaluating the loudness. In order to apply LLz for temporally varying sounds, it was found to be appropriate to use the mean energy level of 1/3 octave band.⁶⁾ The validity of LLz was confirmed in Experiment 2. Especially when the level of the amplitude-modulated sounds increased, *i.e.* the specific frequency component became prominent, the deviation of loudness (PSE) from L_{eq} became large.

5.3 Timbre

The overlapping of AM sounds did not increase the impression of loudness, but decreased it. Does this fact mean that AM sounds are allowable to be included in broad-band noise as air-conditioner noise? In order to examine the effects of AM sounds on the impression of timbre, in Experiment 3 the timbre of broad-band noise mixed with AM sounds was judged using semantic differential. It was found that the timbre was judged to be more metallic as the carrier frequency of AM sounds became higher and to be more clamorous as the carrier frequency became lower. This suggests that the timbre is deteriorated whether the carrier

frequency of AM sounds becomes higher or lower, *i.e.* when AM sounds, high or low, are mixed with broad-band noise. Therefore, such audible AM components should not be included in broad-band noise in order not to deteriorate the timbre.

The three factors were extracted by the factor analysis: they were "metallic" or "unpleasant," "powerful" and "rough." In our previous studies,^{1,15,16)} the three factors, "powerful," "metallic" and "unpleasant," are usually found in the evaluation of various sounds. In Experiment 3, the factors "metallic" and "unpleasant" were combined. This may be due to the fact that when a sound was perceived as being metallic, it always gave unpleasant impression. Therefore these two kinds of impression were not differentiated. Instead, when AM component was prominent, the impression of "rough" became stronger. This may have made the factor "rough" clear. In this study carrier frequency of AM sounds and *S/N* influenced quality of the sound. It would be desirable to examine other factors systematically whether they have effects on the impression of sound in order to find countermeasures for producing good noise quality.

5.4 Evaluation of Air-conditioner Noise

As pointed out by Bergman *et al.*,¹⁷⁾ AM sounds mixed in a complex sound are difficult to be fused in and easy to be detected. When a specific frequency component is included in a broad-band noise and when it is temporally varying, it is easily detected and may deteriorate the timbre of the noise.

Air-conditioner noise as a background noise which is expected to mask other unpleasant noises must not attract the attention by itself, but be neutral and easily habituated to. The findings of the experiments suggest that ideal air-conditioner noise must not contain audible amplitude-modulated components.

6. SUMMARY

(1) AM sounds in broad-band noise were detected when *S/N* was around zero (*S*: the level of AM sound, *N*: 1/3 octave band level of broad-band noise with center frequency corresponding to the carrier frequency of AM sounds). Close examination shows that carrier frequency, modulation frequency and modulation depth have a systematic effect of the detection of AM sounds.

(2) The just detectable level of AM sounds de-

creased as the carrier frequency became higher.

(3) The just detectable level was lower for AM sounds than for pure tones except for modulation frequency of 16 Hz. This suggests that level-fluctuating sounds can easily be detected.

(4) The just detectable level became minimum when the modulation frequency was 1 or 2 Hz. The just detectable level increased as the modulation frequency became higher.

(5) The effect of modulation depth varied depending on the modulation frequency. When the modulation frequency was low, the larger modulation depth produced lower just detectable level. There was little effect of modulation depth when modulation frequency was higher.

(6) The loudness of broad-band noise mixed with AM sounds can be approximately evaluated by *LLz*.

(7) The timbre of broad-band noise mixed with AM sounds was judged to be more metallic as the carrier frequency became higher and to be more clamorous as the carrier frequency became lower. The three factors were extracted by the factor analysis: they were "metallic" or "unpleasant," "powerful" and "rough."

REFERENCES

- 1) S. Namba, S. Kuwano, K. Kinoshita, and K. Kurakata, "Loudness and timbre of broad-band noise mixed with frequency-modulated sounds," *J. Acoust. Soc. Jpn. (E)*, **13**, 49–58 (1992).
- 2) ISO 532, "Acoustics—Method for calculating loudness level" (1975).
- 3) G. von Bismarck, "Sharpness as an attribute of timbre of steady sounds," *Acustica* **30**, 159–172 (1984).
- 4) M. Nishimura and T. Hisajima, "On the evaluation of sound quality for airconditioner noise—pure tone and fluctuating noise," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, 449–450 (1982) (in Japanese).
- 5) E. Zwicker, H. Fastl, U. Widmann, K. Kurakata, S. Kuwano, and S. Namba, "Program for calculating loudness according to DIN 45631 (ISO 532B)," *J. Acoust. Soc. Jpn. (E)* **12**, 39–42 (1991).
- 6) S. Kuwano, S. Namba, and H. Miura, "Advantages and disadvantages of A-weighted sound pressure level in relation to subjective impression of environmental noises," *Noise Control Eng. J.* **33**, 107–115 (1989).
- 7) R. P. Hellman, "Growth rate of loudness, annoyance, and noisiness as a function of tone location within the noise spectrum," *J. Acoust. Soc. Am.* **75**, 209–218 (1984).

- 8) R. Hellman and E. Zwicker, "Magnitude scaling: A meaningful method for measuring loudness and annoyance?," *Proc. Annu. Meet. Int. Soc. Psychophys.*, 123–128 (1990).
- 9) E. Zwicker, "Ueber psychologische und methodische Grundlagen der Lautheit," *Acustica* **8** (Beiheft I), 237–258 (1958).
- 10) E. Zwicker, "Subdivision of the audible frequency range into critical bands (Frequenzgruppen)," *J. Acoust. Soc. Am.* **33**, 248 (1961).
- 11) D. M. Green, *Profile Analysis* (Oxford University Press, Oxford, 1988).
- 12) H. Fastl, "Fluctuation strength and temporal masking patterns of amplitude-modulated broadband noise," *Hear. Res.* **8**, 59–69 (1982).
- 13) E. Zwicker and H. Fastl, *Psychoacoustics* (Springer Verlag, Berlin, 1990).
- 14) S. Namba and S. Kuwano, "Psychological study on L_{eq} as a measure of loudness of various kinds of noises," *J. Acoust. Soc. Jpn. (E)* **5**, 135–148 (1984).
- 15) S. Namba, *The Measurement of Timbre and Its Application* (Oyogijutsu Shuppan, Tokyo, 1992) (in Japanese).
- 16) S. Namba, S. Kuwano, and M. Koyasu, "The measurement of temporal stream of hearing by continuous judgments—in the case of the evaluation of helicopter noise," *J. Acoust. Soc. Jpn. (E)*, **14**, 341–352 (1993).
- 17) A. Bergman, J. Abramson, P. Doehring, and C. J. Darwin, "Spectral integration based on common amplitude modulation," *Percept. Psychophys.* **37**, 483–493 (1985).