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Relationship between Acoustic Parameters and Subjective Human Sensation for Apparel Fabrics

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Abstract. In order to investigate the relationship between acoustic parameters and subjective sensation of apparel fabrics, each frictional sound from 60 different fabrics was recorded and analyzed by Fast Fourier Transform (FFT). Level pressure of total sound (LPT), three coefficients (ARC, ARF, ARE) of auto regressive models, loudness (Z), and sharpness (Z) by Zwickers model were estimated as acoustic parameters. For subjective evaluation, seven sensation (softness, loudness, sharpness, clearness, roughness, highness, and pleasantness) was rated by both semantic differential scale (SDS) and free modulus magnitude estimation (FMME). As the results, the ARC values were positively proportional to both LPT and loudness (Z) values. In both of SDS and FMME, softness, clearness, and pleasantness were negatively correlated with loudness, sharpness, roughness, and highness. In regression models, softness and clearness by FMME were negatively affected by LPT and ARC, while loudness, sharpness, roughness, and highness were positively expected by them.

1. Introduction

Sounds of fabrics have recently attracted both researchers and manufacturers involved in textiles and apparel because fabric sounds have been concerned to affect the sensorial comfort of clothing. Subjective sensation for fabrics has been concerned to be explained by objective measurements related with it [1]. Sound sensation is considered to be affected by the related physical parameters first of all [2]. Fabric sound have been also studied in terms of its relationship with some of reliable objective acoustic parameters. Most of previous works on fabric sounds [3], [4], [5] have focused on the end uses and fiber types of apparel fabrics considering wear conditions of the fabrics. However more general information on fabric sound sensation related with objective acoustic variables have been not reported yet. It is necessary to identify how objective acoustic parameters are related with subjective sensation for fabric sound in order to give more generalized information to both consumers and manufacturers.

The purpose of this study is to investigate acoustic parameters based on FFT spectra and subjective sensation of diverse apparel fabrics, and to establish prediction models for subjective sensation by acoustic parameters which can be applied to more varied apparel fabrics.

2. Materials and Methods

2-1. Stimuli

The stimuli for this study were sounds of 60 different apparel fabrics commercially available. The fabrics included 7 wool, 8 cellulosic fabrics, 12 silk, 14 polyester, 8 nylon, and 11 blended fabrics of which fabric types were different to one another. Sound of each fabric was generated by the measuring apparatus for fabric noise (MAFN : patent no. 0212605) apparatus used in previous studies [3], [4], [5] which simulated the actual rubbing of clothing in real state. Sound was recorded in an anechoic chamber of which loudness of background noise and cutoff frequency were below 10dB and 63Hz respectively. A powerful microphone (Type 4145, B & K) was used to record the fabric sounds and the sounds were recorded by a DAT data recorder (TEAC Model RD-145T). Recorded sounds were transformed into wave files in a computer for presentation.

2-2. Sound Parameters

Recorded sounds were analyzed in terms of amplitude and frequency by FFT analyzer (model 35670A, HP) to calculate their physical parameters including level pressure of total sound, AR coefficients, and psychoacoustic factors such as loudness(Z) and sharpness(Z).

(1) LPT (Level Pressure of Total Sound)

As physical loudness of each fabric, the value of LPT was calculated as follows:

$$\text{LPT (dB)} = 10 \log 10^{\frac{BL_1}{10} + \cdots + \frac{BL_n}{10}} \qquad (1)$$

BL : Broadband sound level at each frequency

n : $f_{max}/\Delta f$

(2) AR coefficients

Linear trends in frequency with autoregressive (AR) error were fitted to amplitude. The AR functions used in this study were as follows:

$$\tilde{y}_1 = \hat{y}_1, \ t=1 \qquad (2)$$

$$\tilde{y}_t = \hat{\alpha} + \hat{\beta}x_t + \hat{\phi}\check{\varepsilon}_{t-1}, \ t=2, \cdots, n \qquad (3)$$

where, $\check{\varepsilon}_{t-1} = y_{t-1} - \hat{y}_{t-1}$,

$\hat{y}_{t-1} = \hat{\alpha} + \hat{\beta}x_{t-1}$.

$\tilde{y}_t$: estimated value of y (amplitude)

$\hat{y}_1$: estimated value of y (amplitude), when t = 1.

t : frequency order (when t = 1, frequency value is 16Hz, when t = 2, frequency is 32Hz)

x_t : value of tth frequency (when t = 1, frequency is 16Hz.)

$\hat{\alpha}$: constant, named as ARC

$\hat{\beta}$: coefficient of x_t term, named as ARF

$\hat{\phi}$: coefficient of ε_{t-1} term (error term), named as ARE

The ARC, ARF, ARE were considered to characterize the spectral shapes of fabric sounds and were investigated for their relationship with subjective sensation.

(3) psychoacoustic factors

Two psychoacoustic factors, loudness(Z) and sharpness(Z) in Zwicker's models [6] were calculated by use of an software (SDRC-based Sound Quality System Type 3800, B&K). The calculations were based on following functions.

① loudness(Z)

$$N = \sum_{i=0}^{24} N'(i)\Delta z_i$$

$$\Delta z_i = 1 \ bark$$

N : loudness(Z), N': specific loudness

$$N'(z) = N'_0 \left(\frac{1}{s}\right)^k 10^{kL_{TQ}/20dB} \cdot \left[\left(1 - s + s \cdot 10^{\frac{L_E - L_{TQ}}{10dB}}\right)^k - 1\right]$$

$$s = 10^{\left(0.22 - 0.005\frac{z}{bark}\right)} - 1$$

N'_0 : reference loudness (0.068sone/bark)

$L_{EHS(z)}$: excitation.

$L_{E(z)}$: threshold factor

$k = 0.23$

② sharpness(Z)

$$S = c\frac{\int_{0bark}^{24bark} N'(z)g'(z)\,dz}{\ln\left(\frac{\frac{N}{sone}+20}{20}\right)}\,sone$$

$$g'(z) = e^{\frac{0.171z}{bark}}$$

$N'(z)$: partial loudness

$N(z)$: total loudness

$g'(z)$: weighting function

2-3. Subjective Evaluation

(1) Subjects

Male and female college students aged from 18 to 26 volunteered for subjective evaluation. After screening tests a total of 30 students participated in this study.

(2) Screening test

Each candidate for participation were screened for normal hearing. The candidate's auditory threshold on pure tone was determined by a Houghson-Westlake, or "5dB up, 10dB down" procedure [7] using an audiometer (GSI 17, Grason-Stadler, Inc.). After screening thirty candidates (hereafter subjects) were finally determined to be qualified for the evaluation.

(3) Procedures

Each of prerecorded sound of fabrics was presented to each subject wearing headphone (Philips, SBC HP 110) connected to a computer which had wave files of the fabric sound. After each presentation the subjects were asked to answer the questionaire relating to their subjective sensation of the sound. At first they rated their sensation by semantic differential scale (SDS), and then asked to use free modulus magnitude estimation (FMME) for rating the sensation of each sound by giving a number corresponding to the perceived magnitude of the sound sensation.

(4) Sound sensation descriptors

Sound sensation descriptors in a previous work [5] were used. Table 1 shows the descriptors for both SDS and FMME.

Table 1. Descriptors for sound sensation

Sound Sensation	Descriptors (S)		Descriptors (F)
	-3	+3	
S_1	Hard	Soft	Softness
S_2	Quiet	Loud	Loudness
S_3	Dull	Sharp	Sharpness
S_4	Obscure.................	Clear	Clearness
S_5	Smooth..................	Rough	Roughness
S_6	Low	High	Highness
S_7	Unpleasant	Pleasant	Pleasantness

S means semantic differential scale
F means free modulus magnitude estimation

2-4. Experimental design and data analysis

A balanced incomplete block design was selected for the subjective experiment. By the design each subjects rated 6 different sound stimuli in random order and each stimulus was scored repeatedly by 3 different subjects.

Before data analysis, FMME data collection were transformed by a procedure described in a previous work [8] to eliminate both inter-subject variance and intra-subject variance.

Pearson's correlation coefficients were obtained among sound parameters and subjective sensation respectively. For estimating the relationship between fabric sound parameters and subjective sensation, curved linear regression models were established for each sensation.

3. Results

3-1. Sound parameters of fabrics

Table 2 gives the values for the six sound parameters for fabrics. Correlation coefficients among the parameters are also shown in Table 3. The values for LPT ranged from 36.6dB (S4. satin) to 64.8dB (S11. brocade). This range corresponds to level of living room (30~40dB) and normal conversation (60~70dB). Among AR coefficients. ARC showed a variety of ranges from 23.15 (S7) to 51.56 (N4). The LPT and ARC showed a high correlation between them. Loudness(Z) ranged from 0.2sone (S4) to 3.8sone (S11). It was highly correlated with ARC as well as with LPT. This supports the previous study [3] suggesting that ARC could be applied as the parameter for fabric sound loudness.

The highest values for sharpness(Z) was 5.2acum (B3) while the lowest 2.4acum (S10). They were higher than those for woodwinds reported as 0.5~2.0acum. [9]. Sharpness(Z) seemed not to be concerned to the parameters such as LPT. ARC. and loudness(Z). It showed a significant correlation with ARE.

3-2. Subjective sensation for fabric sound

Each sensation score for each fabric sound was obtained. Correlation coefficients among the subjective sensation by both SDS and FMME are presented in Table 4. All of coefficients among the sensation were significant. Semantic and magnitude estimation reached a quite agreement in the relationship among the sensation. In both two experiments. softness. clearness. and pleasantness were positively correlated with one another. This means that fabric sounds rated as softer were also evaluated as clearer and

Table 2. The values for sound parameters of fabrics

S*	LPT (dB)	AR coefficients			Psychoacoustic factors	
		ARC	ARF	ARE	Loudness(Z) (sone)	Sharpness(Z) (acum)
W1	53.0	38.6	-0.0025	0.9984	1.2	4.3
W2	55.0	37.9	-0.0024	0.9984	2.0	4.5
W3	52.9	38.9	-0.0025	0.9979	2.2	4.2
W4	54.3	41.0	-0.0027	0.9985	1.8	4.5
W5	48.7	38.5	-0.0027	0.9983	1.0	4.8
W6	50.0	39.6	-0.0029	0.9987	0.7	4.5
W7	53.6	39.0	-0.0026	0.9985	1.3	4.6
C1	50.4	36.3	-0.0026	0.9984	1.1	3.6
C2	50.1	37.0	-0.0029	0.9986	0.8	3.8
C3	47.9	35.0	-0.0025	0.9977	0.6	3.9
C4	51.2	35.3	-0.0026	0.9984	1.1	3.4
C5	51.2	32.9	-0.0025	0.9982	1.1	3.1
C6	52.0	40.9	-0.0031	0.9988	0.7	3.4
C7	49.3	36.3	-0.0030	0.9987	0.6	3.1
C8	51.1	35.9	-0.0027	0.9984	1.1	3.6
S1	52.5	27.0	-0.0025	0.9982	0.3	3.7
S2	41.2	29.6	-0.0026	0.9983	0.5	4.9
S3	44.1	31.1	-0.0026	0.9984	0.7	4.4
S4	36.6	25.8	-0.0028	0.9983	0.2	3.7
S5	47.5	37.8	-0.0029	0.9989	0.5	4.1
S6	49.3	37.8	-0.0029	0.9985	0.8	3.6
S7	40.2	23.2	-0.0024	0.9951	0.2	3.7
S8	40.0	24.0	-0.0024	0.9970	0.3	3.8
S9	42.8	26.9	-0.0026	0.9970	0.4	3.7
S10	53.8	36.0	-0.0030	0.9971	0.7	2.4
S11	64.8	49.0	-0.0027	0.9992	3.8	3.7
S12	50.3	32.7	-0.0022	0.9980	0.7	3.9
P6	52.7	38.5	-0.0025	0.9987	1.1	5.1
P1	49.6	35.1	-0.0024	0.9985	1.0	4.1
P2	42.4	30.9	-0.0029	0.9986	0.3	4.0
P7	51.5	38.9	-0.0024	0.9982	1.9	4.4
P9	47.2	35.6	-0.0027	0.9987	0.6	5.0
P3	46.9	35.9	-0.0026	0.9985	0.7	4.9
P8	50.8	37.7	-0.0026	0.9985	1.3	4.8
P4	49.1	34.2	-0.0027	0.9988	0.6	4.4
P5	37.7	26.1	-0.0027	0.9987	0.2	3.7
P10	62.3	46.5	-0.0023	0.9986	3.0	4.7
P11	42.7	28.6	-0.0028	0.9983	0.3	3.7
P12	61.3	40.9	-0.0026	0.9968	2.1	2.5
P13	51.4	41.7	-0.0029	0.9985	1.1	3.7
P14	58.4	42.7	-0.0027	0.9984	2.0	3.2
N1	61.9	47.8	-0.0024	0.9986	3.4	4.4
N2	61.4	43.2	-0.0024	0.9980	2.7	2.9
N3	59.8	49.4	-0.0026	0.9987	2.7	4.6
N4	61.2	51.6	-0.0027	0.9988	3.0	4.1
N5	56.4	39.6	-0.0021	0.9985	2.4	4.5
N6	63.8	45.0	-0.0023	0.9988	3.9	4.6
N7	60.6	48.7	-0.0025	0.9986	2.5	3.6
N8	49.6	35.1	-0.0020	0.9976	1.5	4.1
B1	48.2	38.3	-0.0027	0.9986	1.0	5.1
B2	56.3	42.0	-0.0026	0.9987	1.5	4.0
B3	53.8	39.0	-0.0027	0.9988	1.3	5.2
B4	45.5	30.9	-0.0025	0.9984	0.7	5.0
B5	56.2	41.6	-0.0026	0.9987	1.4	5.1
B6	43.5	31.0	-0.0027	0.9987	0.4	5.0
B7	60.9	40.1	-0.0025	0.9994	2.2	4.4
B8	51.6	40.1	-0.0030	0.9992	1.3	4.9
B9	57.9	48.9	-0.0030	0.9988	2.0	4.7
B10	46.4	35.3	-0.0027	0.9985	0.7	5.1
B11	56.6	44.6	-0.0029	0.9988	1.4	5.2

* means specimens

W indicates wool fabrics. C cellulose fabrics. S silk fabrics. P polyester fabrics. N nylon fabrics. and B blended fabrics.

Table 3. Correlation coefficients among sound parameters

Variables	LPT	ARC	ARF	ARE	Loudness(Z)
LPT					
ARC	0.85**				
ARF	0.16	-0.18			
ARE	0.15	0.46**	-0.54**		
Loudness (Z)	0.87**	0.82**	0.23	0.24	
Sharpness (Z)	0.04	0.23	-0.03	0.44**	0.07

** means $p < .01$

Table 4. Correlation coefficients among the sound sensation

		Soft-ness	Loud-ness	Sharp-ness	Clear-ness	Rough-ness	High-ness
Soft-ness	S						
	F						
Loud-ness	S	-0.55**					
	F	-0.71**					
Sharp-ness	S	-0.41**	0.54**				
	F	-0.40**	0.47**				
Clear-ness	S	0.55**	-0.67**	-0.44**			
	F	0.31*	-0.47**	-0.27*			
Rough-ness	S	-0.65**	0.81**	0.59**	-0.70**		
	F	-0.58**	0.65**	0.49**	-0.49**		
High-ness	S	-0.42**	0.44**	0.39**	-0.31*	0.52**	
	F	-0.50**	0.59**	0.39**	-0.38**	0.48**	
Pleasant-ness	S	0.57**	-0.71**	-0.47**	0.59**	-0.78**	-0.39**
	F	0.38**	-0.54**	-0.28*	0.33**	-0.40**	-0.28*

S means semantic differential scale
F means free modulus magnitude estimation
* means $p < .05$
** means $p < .01$

more pleasant. The other hand, the three sensation showed negative correlation with loudness, sharpness, roughness, and highness. This resulting implies that fabrics scored as louder, sharper, rougher, and higher showed less sensation for softness, clearness, and pleasantness.

3-3. Relationship between fabric sound parameters and subjective sensation

To predict subjective sensation for fabric sound by the physical parameters, curved linear regression models for each sensation measured by both SDS and FMME were established. As results, prediction models for all of sensation by magnitude estimation had higher R^2 than by semantic portion. Relationships between fabric sound parameter and subjective sensation in FMME are given in Fig. 1~Fig. 7 by both regression curves and equations.

For softness, fitting curve had the highest R^2 in which relationship between softness by FMME and LPT was estimated (Fig. 1). The equation indicated that fabrics with higher LPT values were regarded as less softer by subjects.

Loudness was also regressed showing higher R^2 in FMME than in SDS and was explained by LPTas shown in Figure 2. The LPT affected positively subjective loudness for fabric sound.

The ARC was found to be more acceptable predictor for sharpness by FMME than any others

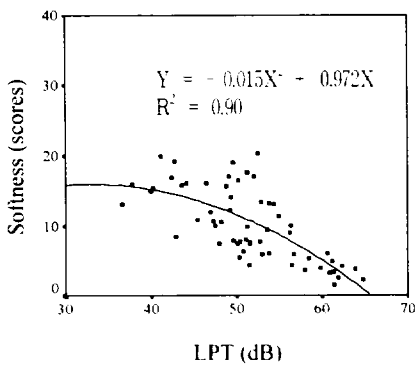

Fig. 1. Relationship between subjective softness by FMME and LPT.

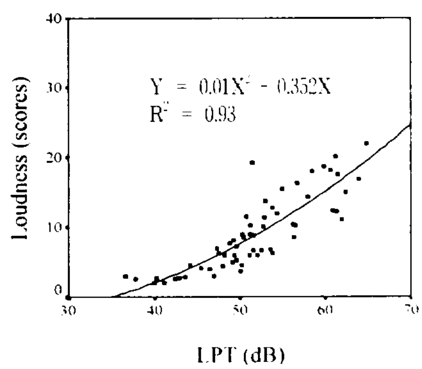

Fig. 2. Relationship between subjective loudness by FMME and LPT.

(Fig. 3). The models indicated that fabrics with higher ARC generated sound subjectively sharper.

The ARC described clearness by FMME showing the highest R^2 of all parameters (Fig. 4). Clearness seemed to be affected negatively by ARC considered to indicate physical loudness.

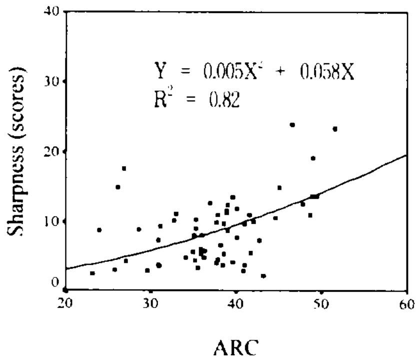

Fig. 3. Relationship between subjective sharpness by FMME and ARC.

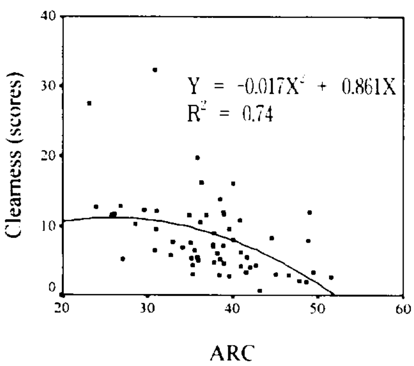

Fig. 4. Relationship between subjective clearness by FMME and ARC.

As expected, the most acceptable models for roughness and highness were also established by LPT and ARC as the predictors respectively (Fig. 5 & Fig. 6).

For pleasantness, LPT was the most reliable predictor. The model showed that fabrics generating sound with higher LPT was evaluated as less pleasant. However R^2 of the equation was not high such as those of the equation for other sensation.

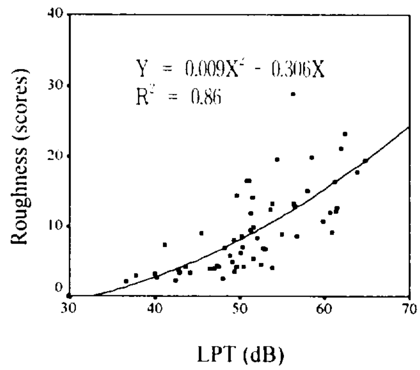

Fig. 5. Relationship between subjective roughness by FMME and LPT.

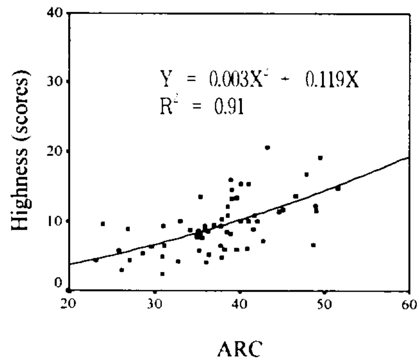

Fig. 6. Relationship between subjective highness by FMME and ARC.

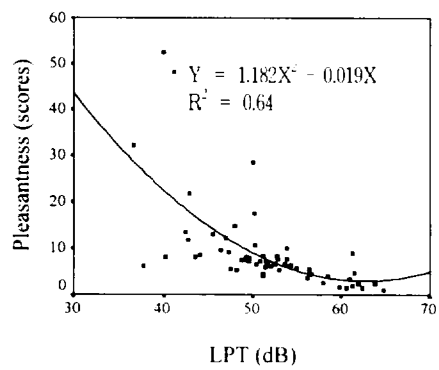

Fig. 7. Relationship between subjective pleasantness by FMME and ARC.

It means that pleasantness is more composite sensation so that physical parameters concerned with sound loudness such as LPT are not enough to describe it well.

4. Conclusion

This study was carried out to estimate the relationship between acoustic parameters from frictional sounds of apparel fabrics and subjective sensation by suggesting the regression model for predicting the sensation by acoustic parameters. Fabric sound sensation including softness, loudness, sharpness, roughness, clearness, highness were affected by loudness-related physical parameters such as LPT and ARC. This implies that consumers generally evaluate fabric sound subjectively considering sound loudness. However pleasantness for fabric sound was not explained reliably by the parameters. Subjective pleasantness needs to be investigated according to the end uses and fiber type of fabrics for obtaining more explainable models for it in future works.

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