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Study on the Friction Sound Properties of Natural-Fiber Woven Fabrics

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Abstract

An innovative frictional sound automatic measuring system (FSAMS) was designed and used in this study to investigate the frictional sound generated when natural-fibre woven fabrics are rubbed together. Frictional sound measurements made using the automatic FSAMS were compared with those from a manual frictional sound measuring system (Manual FSAMS). The frictional sounds of four natural-fiber woven fabrics (i.e., cotton, linen, silk, and wool) were recorded; the Fast Fourier Transform method was used to convert time domain signals into frequency domain signals, and the maximum sound amplitude (MSA) and level pressure of the total sound (LPTS) of cotton, linen, silk, and wool were calculated. The results of a t test, analysis of variance, data reproducibility, and cluster spectrums measured from the four natural-fiber woven fabrics were compared for the two test equipment systems. The results from the t test and analysis of variance showed significant differences in the MSA and LPTS measured. Data reproducibility was superior to the automatic FSAMS compared with the manual FSAMS, and the cluster spectrums were more readily distinguishable.

Key words: *fabric sound automatic measuring system, sound level pressure, fast Fourier transform.*

Introduction

Consumers have grown increasingly demanding about their clothing products, hence in addition to fabric quality, increasing emphases have been placed by manufacturers in quality evaluation on both the functionality of clothing products and on sensory evaluation [1-3].

Fabric frictional sound is generated when fabrics are rubbed together. These sounds are closely related to the fundamental structures and mechanical properties of the fabric The subjective description of sound qualities such as loudness, tone and timbre individually rely on single or multiple physical parameters. Loudness primarily involves frequency-related sound pressure and pitch. Audible human ear frequencies range from 20 Hz to 20 kHz, and, for example:

- musical performance frequencies range approximately from 100 Hz to 10 kHz;
- most people's speech falls within a frequency range of 100 Hz and 5 kHz;
- fabric frictional sounds in the range between 100 Hz and 5 kHz can be clearly distinguished [4].

In 2000 Yi and Cho [5] conducted a study on fabric frictional sounds using a sound generator along with the fast Fourier transform (FFT) method to convert fabric friction time domain signals into frequency domain signals and calculated the respective level pressure of the total sound (LPTS). Additionally they used the autoregressive (AR) model to evaluate fabric friction sounds and clustered the LPTS and AR model parameters. Also in 2000, Yi and Cho [6] took five knitted/ woven fabric materials and used FFT to record their respective friction sounds and calculate their LPTs. In 2002, Yi and Cho [7] used a novel measuring apparatus for fabric noise, developed a wool fabric sound evaluation system and combined FFT, the AR model, and Zwicker's psychoacoustic models into an integrated wool fabric evaluation system. In the same year, Kim and Cho [8] published their study on the influence of various silk fabric woven structures on sound parameter variations.

In 2003, Kim and Cho [9] studied the influence of various fundamental fabric structures and fiber thicknesses on friction sound variations. They used seven sample fabrics, three fiber thicknesses, and various knitted structures to compare their psychoacoustic responses. In 2007, Na and Cho [10] used fixed frequencies through the reverberation room method to test the sound absorption coefficients of five microfiber fabrics and one ordinary fiber fabric. The results showed that microfibers were superior to ordinary fibers in sound absorption. In 2009, Cho and Kim [11] studied the friction of weft-knitted fabrics. The purpose of their study was to investigate the correlation between the frictional sound and mechanical properties of knitted fabrics focusing on the influence of various knitting structures (i.e., plain, ribbed, half-cardigan, and half-milano stitch) and the mechanical properties of the fabrics as measured by the Kawabata Evaluation System. In 2012, Park and Cho [12] tested the fabric frictional sound of knitted, woven, and vapour-permeable water-repellent fabrics using a measuring apparatus for fabric noise, whilst Cho and Cho [13] studied the frictional sounds of PU-nanoweb and PTFE vapour-permeable water-repellent laminated fabrics on people engaging in physical activities.

Most studies on fabric frictional sounds investigating either single or composite fiber materials have not considered the possibility of variations in the frictional sound measured that may arise from the use of different measuring instruments. Thus an automatic friction sound test equipment (FSAMS) system was developed in this study to investigate the influence of two different equipment types (one manually operated and the other automatic) on the woven fabric frictional sound measured. A feature of the equipment developed in this study is its reproducablity in recording the sounds created through friction in a controlled manner. On the FSAMS system, the sample fabrics are moved by a sliding device, which can control both the velocity of movement of one piece of fabric over another and the distance travelled. The fabric fixtures for holding each piece in a controlled and reproducible way during each test were also designed to ensure the reproducibility of experimental data.

Experimental

Experimental materials

A number of commercially available woven fabrics were selected as test specimens. They included fabrics for men's and women's suits as well as men's and women's shirts. Samples of four natural-fiber woven fabrics, namely cotton, linen, silk, and wool, were used in this work: 42 cotton, 20 linen, 16 silk and 46 wool fabric pieces.

Specifications of the samples are listed in ***Table 1***. Three samples tested were taken from each piece of fabric and trimmed to a 20 cm × 20 cm square along the warp and weft directions. All finished fabrics were used in men's and women's clothes, and purchased from the present market. Scouring, bleaching, dyeing and setting were applied in the above fabric finishing. All samples were kept for 24 hours at 20±2°C and 65±2% RH prior to the taking of measurements. Specifications of the samples are listed in ***Table 1***. Three samples were taken from each piece of fabric and trimmed to a 20 cm × 20 cm square aligned with the warp and weft directions.

Table 1. *Properties of the four natural-fiber woven fabrics tested.*

Fabric		Warp density, ends/cm	Weft density, picks/cm	Thickness*, mm	Weight, g/m²
Cotton	MAX	67.7	40.9	0.68	186.9
	MIN	19.3	18.5	0.36	102.1
	MEAN	45.1	27.1	0.52	140.2
	S.D.	11.4	6.5	0.08	26.1
Linen	MAX	44.1	28.3	0.95	280.7
	MIN	9.4	12.6	0.40	101.5
	MEAN	25.3	21.3	0.62	163.2
	S.D.	7.9	4.1	0.14	47.4
Silk	MAX	68.5	59.8	0.72	180.7
	MIN	22.0	18.9	0.16	55.1
	MEAN	40.8	35.4	0.34	91.7
	S.D.	14.8	10.1	0.18	33.1
Wool	MAX	47.2	44.1	0.80	272.0
	MIN	18.9	17.3	0.42	152.6
	MEAN	33.3	31.7	0.53	192.6
	S.D.	6.4	5.7	0.10	27.8

* *Thickness is measured as being under 0.5 cN/cm².*

Experimental methods

In this study, both manual and automatic FSAMS systems capable of reproducibly measuring the frictional sounds generated by the fabrics were developed.

Manual FSMS

The test equipment comprised an acoustic enclosure (450 mm × 450 mm × 250 mm), an integrating-averaging sound level meter (A&D Type 6226, Japan), a spectrum analyser (NI Model 9234 National Instruments, USA) and a personal computer. The overall structural arrangement of the test instruments is shown in ***Figure 1*** [15, 18], and the experimental process diagram is shown in ***Figure 2*** [17, 20]. The specifications are as follows:

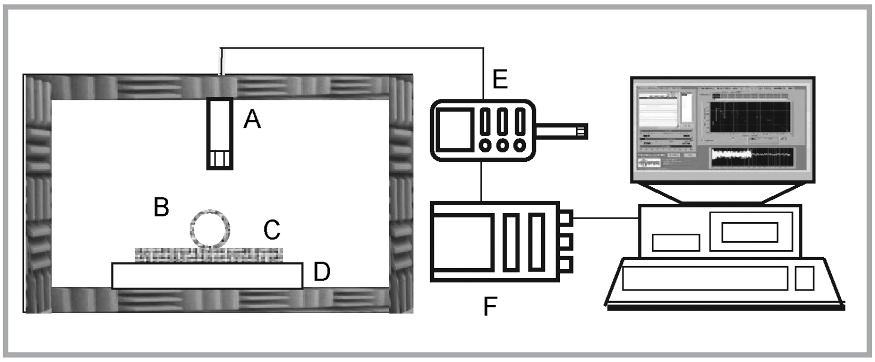

Figure 1. *Schematic diagram of the manual FSAMS system for fabric noise; A: microphone, B and C: test fabric, D: base plate, E: sound meter, F: spectrum analyser level meters.*

a) The integrating-averaging sound level meter

An A&D Type 6226 meter, capable of measuring analogue and digital signals ranging from 28-130 dB (A), was employed. The front-end consisted of a 1/2 electret condenser microphone.

b) The spectrum analyser

A National Instruments Model 9234 spectrum analyser with a 24-bit resolution, 102 dB dynamic range, antialiasing filter, and four simultaneously-sampled analogue input channels (with a ± 5 V input range) was used; each channel had the capacity to sample up to a rate of 51.2 kHz/s.

c) The acoustic enclosure

The acoustic enclosure (450 mm × 450 mm × 250 mm) used in the manual FSAMS system was a box with insulation material inside. The object of the box is simply for manually made frictional sound. It had two holes with sound insulated. The hands can strengthen the box and make friction sound with controlled speed.

d) The trained operator

All of the tests should be conducted by the same person, who, before running tests, must practice key operations: first, mounting of the test fabics in a repro-

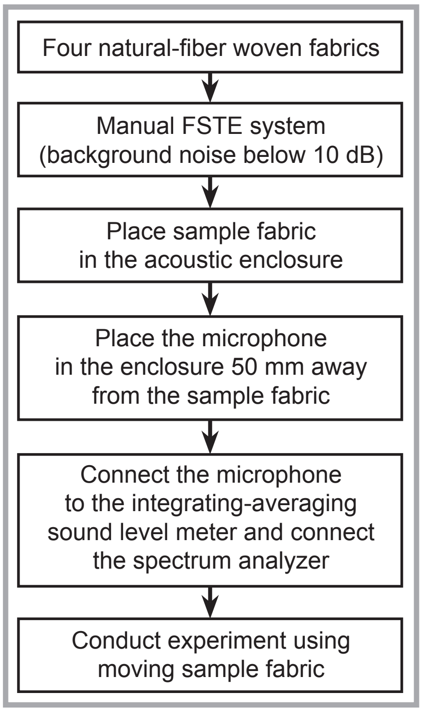

Figure 2. *Flow chart of the manual FSAMS system.*

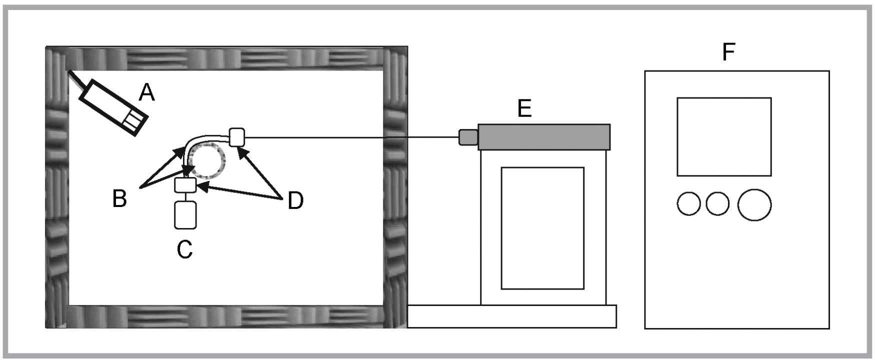

Figure 3. Schematic diagram of the automatic FSAMS system for fabric noise; A: microphone, B: fabric, C: load, D: fixture, E: sliding device, F: Programming logic control (PLC).

ducible fashion, and second moving the sample fabrics with the friction handles in such a way as to apply a consistent, identical force during each of the friction experiments.

e) The test procedure

The background noise must be less than 10 dB when operating the manual FSAMS. During the experiments, the sample fabrics were fixed within the acoustic enclosure, and then the integrating-averaging sound level meter microphone was also placed within the acoustic enclosure. The microphone was placed at a distance of 50 mm from the sample fabric and the integrating-averaging sound level meter was connected to the spectrum analyzer to convert the sound signals recorded by the integrating-averaging sound level meter into experimental data through spectrum analysis. The spectrum analyzer was then linked to a computer to enable the time and frequency domain signals during friction tests to be observed.

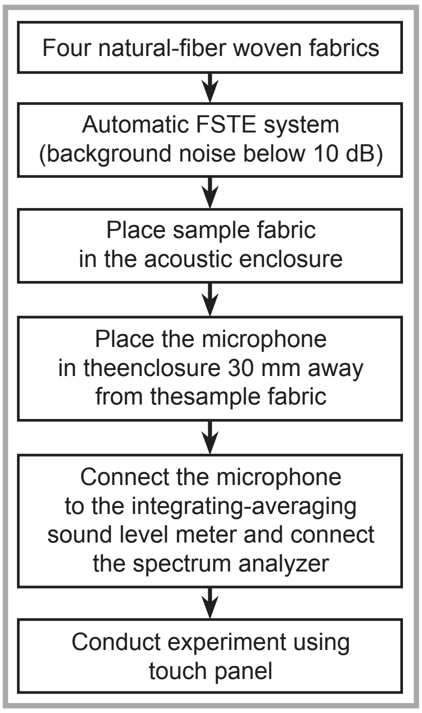

Figure 4. Flow chart of the Automatic FSAMS system.

Automatic FSAMS

The test equipment included a programmable logic controller (PLC) ECMA-C20604FS, a human machine touch screen interface (DOP-B05S100), a fabric-friction sliding device, an acoustic enclosure (950 mm × 600 mm × 940 mm), stationary fixtures, moving fixtures, an integrating-averaging sound level meter, spectrum analyzer and personal computer. The overall structural diagram is shown in ***Figure 3***, and the experimental process flow diagram is shown in ***Figure 4*** [14-19].

The primary purpose of this instrument is to generate fabric friction sounds. The individual functions are described as follows:

a) Programmable logic controller ECMA-C20604FS

A Delta Electronics ASD-B2 ECMA-C20604FS PLC server controller was used, capable of adjusting the moving velocities, distances and patterns (i.e., back-and-forth and successive reciprocation motions) of the fabric-friction sliding device. The moving velocities and distances could be varied from 0-500 mm/s and 0-70 mm, respectively.

b) Human-machine touch screen interface (DOP-B05S100)

A Delta Electronics DOP-B series B05S100 touch screen monitor was used. A microcomputer controller program capable of managing fabric friction velocities and distances was designed and integrated with the touch-screen.

c) Fabric fixtures and moving fixtures

The fixtures (i.e., stationary and moving) used in this study were those described and patented by the laboratory [14, 17]. The patented fixtures are capable of securing the fabrics, maintaining their levelness, and, through evenly distributing the applied stresses, preventing the deformation and slanting of the fabrics.

d) The integrating-averaging sound level meter

An A&D Type 6226 meter, capable of measuring analogue and digital signals ranging from 28-130 dB (A), was employed, the the front-end consisting of a 1/2 electret condenser microphone in a similar arrangement to that used in the manual FSAMS.

e) The spectrum analyzer

As was the case with the manual FSAMS, a National Instruments Model 9234 spectrum analyser with a 24-bit resolution, 102 dB dynamic range, antialiasing filter, and four simultaneously-sampled analogue input channels (with a ± 5 V input range) was used; each channel had the capacity to sample up to a rate of 51.2 kHz/s.

f) The acoustic enclosure

The acoustic enclosure (950 mm × 600 mm × 940 mm) is a box with insulation material inside walls; it has some fixed and mobile fixtures as well as counterweights for making fabric friction sound. Inside the enclosure, the microphone and cables were put near the friction sound generation position for collecting the sound signal. The acoustic enclosure used in the automatic MSA equipment was designed not only to prevent external noise from interfering with the accuracy of experiments but also to allow the installation, removal and exchange of a variety of audio reception instruments, thereby enabling equipment-suitability tests to be conducted.

g) The experimental procedure

All experiments were conducted within the acoustic enclosure. Sample fabrics were moved by a mechanical sliding device capable of providing controlled movement over a range of velocities (0-500 mm/s) and stroke distances (0-70 mm). In terms of sample fabric fixtures, the particular design suited to the type of material under test was selected, i.e. for cotton, linen, silk, or wool (necessary to keep the fabric's reproducibly taut during fabric friction experiments, and thereby minimize experiment errors).

During the experiments, sample fabrics were laid flat before being secured to the stationary and moving fixtures. The microphone of the integrating-averaging sound level meter was installed within the acoustic enclosure at a distance of 30 mm from the sample fabric. The integrating-averaging sound level meter was connected to the spectrum analyzer (to convert the sound signals into sound data through spectrum analysis) and the spectrum analyzer was linked up to the computer to enable the time and frequency domain signals of the frictional sounds to be observed. The moving velocities and distances of the sample fabric were then set (in the case of the experiments reported here, the fabric frictional-stroke distance was kept the same for all tests at 50 mm).

Fabric frictional sound parameters

a) The LPTS

The value in LPT represents the loudness of the loudness physical parameter, and accounts for both the human audible frequencies and limitations of the integrating-averaging sound level meter (16-20 kHz). Thus the LPT calculation range was set between 16–20 kHz [20].

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

BL represents the broadband level.

b) The MSA

The MSA value represents the corresponding frequency position of the maximum decibel on the spectrum. Corresponding decibel values at ±100 Hz positions of the MSA were also averaged.

Statistical analysis

ANOVA analysis was used to compare the differences among the frictional sound properties of the four natural-fiber woven fabrics. A *t*-test analysis was performed to evaluate the difference between the frictional sound parameters of two fabrics. The contribution of selected parameters was evaluated using the partial *F*-test criterion method [21-25]. SPSS 18 was used in the ANOVA analysis and *t*-test.

Table 2. *T test of LPT of the four natural-fiber woven fabrics in four clusters.*

Session	Group	Number	Mean	t-value	p-value
Session 1	Cotton -A	42	56.79	-24.339	0.000
	Cotton-M	42	81.81		
Session 2	Linen- A	20	54.92	-20.075	0.000
	Linen- M	20	77.44		
Session 3	Silk-A	16	57.84	-10.215	0.000
	Silk- M	16	77.06		
Session 4	Wool-A	46	63.58	-18.813	0.000
	Wool- M	46	71.97		

* *M:Manual FSAMS, A:Automatic FSAMS.*

Table 3. *ANOVA test for LPT among four clusters of the four natural-fiber woven fabrics.*

Cluster* fabric	1		2		3		4		F–test	p
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.		
Cotton-A	50.29	1.12	54.09	1.49	58.61	2.49	64.81	5.11	115.14	0.000
Cotton-M	74.22	2.87	79.71	1.23	83.43	1.00	87.54	1.36	97.41	0.000
Linen-A	51.92	0.90	53.60	0.43	55.96	0.45	57.02	0.24	76.95	0.000
Linen-M	69.25	2.22	75.49	1.23	79.67	1.38	83.46	0.42	54.95	0.000
Silk-A	51.89	1.87	56.74	1.12	59.57	1.29	62.93	0.67	34.81	0.000
Silk-M	66.53	2.92	73.82	2.05	81.50	1.73	83.82	0.11	50.63	0.000
Wool-A	60.33	0.43	61.91	0.65	64.98	0.72	67.35	0.71	210.17	0.000
Wool-M	66.94	1.31	70.09	1.10	73.37	0.92	77.46	1.05	158.35	0.000

* *Clusters 1-4 represented groups of the smallest to the largest LPT, respectively.*

Results and discussion

T test and ANOVA for data measured using the SPSS10 application software and automatic FSAMS systems

In this study, a *t* test was used to evaluate whether the frictional sound values measured from the four natural-fiber woven fabrics using the manual and automatic FSAMS systems showed any significant differences (***Table 2***). The *t*-test results indicated that the frictional sound values measured from the four woven fabrics using the manual and automatic FSAMS systems exhibited significant differences ($p = .000$, $p < .05$). Additionally ANOVA was used to compare the outputs from the manual and automatic FSAMS systems for the four natural-fiber woven fabrics to determine whether significant differences existed between the means of each group. ***Table 3*** shows that the results were significant ($p < .001$), which means that the frictional sounds of the four natural-fiber woven fabrics as measured by the manual and automatic equipment exhibited differences. The *f* statistic of the values measured using the automatic FSAMS for cotton, linen and wool were higher than that using the manual FSAMS (with the exception of the silk fabric). Thus LPT differences measured using the automatic FSAMS were larger than those measured using the manual equipment; this occurred because the automatic FSAMS had comparatively superior data reproducibility.

Reproducibility of frictional sound data measured by the automatic FSAMS systems

Five pieces of cotton, linen, silk and wool were used as samples in the reproducibility experiment, for which a test was conducted three times on each sample fabric. Average LPT values and coefficients of variation (CV%) were calculated for the three experiments (***Table 4***). ***Table 4*** shows that the CV% values measured using the manual FSAMS for cotton, linen, silk and wool ranged from 2.45%-5.05%, 1.39%-3.83%, 1.47%-3.66% and 1.47%-2.77%, respectively. By contrast, the CV% values measured using the automatic FSAMS for cotton, linen, silk and wool ranged from 0.64%-2.27%, 0.53%-2.22%, 0.13%-1.43% and 0.40%-1.86%, respectively. Thus the CV% values measured using the manual and automatic FSAMS systems ranged from 1.39%-5.05% and 0.13%-2.27%, respectively, and the CV% values for cotton, silk and wool measured using the automatic FSAMS were all less than those using the manual FSAMS. This result shows that although CV% values were not large, all CV% values yielded from the automatic FSAMS were comparatively smaller. Thus the automatic FSAMS produces smaller errors than the manual FSAMS, whereas the frictional sounds from the manual FSAMS were all larger than those from the automatic FSAMS. Higher frictional sounds emerge from manual FSAMS tests because the manual FSAMS is influenced by both human factors and ambient noises, and the manual arrangement has to be

Table 4. *Experimental results of the friction sound by the manual and automatic FSAMS systems.*

	Friction sound			
	Manual FSAMS system		Automatic FSAMS system	
Sample	LPT (dB)	CV%	LPT (dB)	CV%
C01	73.84	2.89%	52.80	0.64%
C02	76.32	2.45%	51.65	2.27%
C03	83.30	2.99%	60.10	1.96%
C04	78.98	5.05%	63.84	1.89%
C05	86.78	4.17%	60.67	0.76%
L01	79.99	2.06%	52.26	1.03%
L02	76.41	3.83%	55.56	2.22%
L03	77.65	1.39%	55.04	1.04%
L04	79.77	1.78%	55.29	0.53%
L05	81.54	2.75%	56.93	1.74%
S01	71.28	1.78%	52.05	0.49%
S02	72.98	3.66%	57.80	0.13%
S03	81.11	1.69%	55.98	1.20%
S04	83.86	1.47%	58.57	0.67%
S05	81.80	1.93%	63.96	1.43%
W01	66.94	2.77%	62.52	1.86%
W02	67.68	2.22%	56.61	1.58%
W03	71.68	1.57%	64.38	0.90%
W04	73.52	1.79%	65.29	1.29%
W05	77.08	1.47%	66.63	0.40%

Table 5. *LPT of the four natural-fiber woven fabrics in four clusters.*

		Manual FSAMS system		Automatic FSAMS system	
Fabric	Cluster	LPT	S.D	LPT	S.D
Cotton	Cluster 1	74.22	2.87	50.29	1.12
	Cluster 2	79.71	1.49	54.09	1.23
	Cluster 3	83.43	1.16	58.61	1.01
	Cluster 4	87.54	2.49	64.81	1.36
Linen	Cluster 1	69.25	2.22	51.91	0.90
	Cluster 2	75.49	1.23	53.60	0.43
	Cluster 3	79.67	1.38	55.95	0.45
	Cluster 4	83.46	0.42	57.02	0.24
Silk	Cluster 1	66.53	2.92	51.89	1.87
	Cluster 2	73.81	2.05	56.74	1.12
	Cluster 3	81.50	1.73	59.57	1.29
	Cluster 4	83.82	0.67	62.93	0.12
Wool	Cluster 1	66.93	1.31	60.33	0.43
	Cluster 2	70.09	1.10	61.91	0.65
	Cluster 3	73.37	0.92	64.98	0.72
	Cluster 4	77.46	1.05	67.35	0.71

partly open to allow the operator to move the fabric, thereby resulting in comparatively larger frictional sounds combined with experimental errors, whereas the automatic FSAMS was free from human factors and the effects of external noise.

Cluster comparison of LPTs of the four natural-fiber woven fabrics

To clearly cluster the friction sound data tested using the FSAMS systems, the mean and standard deviations (SD) of LPTs were used as bases for distinguishing the fabrics. The data were divided based on fabric type and the FSAMS systems used, either manual or automatic (***Table 5***). Clusters 1-4 represented groups of the smallest to the largest LPTs, respectively.

Manual FSAMS: The mean values of LPT from Clusters 1-4 for cotton, linen, silk and wool measured using the manual FSAMS were as follows: Cotton: 74.22, 79.71, 83.43, and 87.54 dB; Linen: 69.25, 75.49, 79.67, and 83.46 dB; Silk: 66.53, 73.81, 81.50, and 83.82 dB; and Wool: 66.93, 70.09, 73.37, and 77.46 dB. The SDs measured using the manual FSAMS for the four fabrics ranged from 0.42–2.92.

Automatic FSAMS: The mean LPT values from Clusters 1-4 for cotton, linen, silk and wool measured using the automatic FSAMS were, respectively, as follows: Cotton: 50.29, 54.09, 58.61, and 64.81 dB; Linen: 51.91, 53.60, 55.95, and 57.02 dB; Silk: 51.89, 56.74, 59.57, and 62.93 dB; and Wool: 60.33, 61.91, 64.98, and 67.35 dB. The SDs measured using the automatic FSAMS for the four fabrics ranged from 0.43-1.87.

Although the SDs were not large in either case, the LPTs measured using the automatic FSAMS were considerably smaller than those for the manual FSAMS. Thus the automatic FSAMS yielded smaller errors than the manual FSAMS, and the frictional sounds measured by the manual FSAMS were all greater than those measured by the automatic FSAMS.

Cluster spectrums for the friction sounds of the four natural-fiber woven fabrics

Frictional sound cluster spectrums of cotton, linen, silk and wool fabrics identified in Clusters 1-4 were obtained from the manual and automatic FSAMS systems (***Figures 5*** and ***6***). When emphasis was placed on the clusters for the automatic FSAMS, the selections of manual and automatic Clusters 1 and 4 of the linen and silk fabrics were different. Thus in addition to selecting identical fabrics for the manual and automatic FSAMS clusters, fabric spectrums were also added to Cluster 4 (L05) and Cluster 1 (S05) in ***Figures 5b*** and ***5c***, respectively.

Figure 5 shows the differences in the spectrums of the cotton, linen, silk, and wool fabrics when using the manual FSAMS. This result showed that:

1) the MSA of the cotton fabric measured using the manual FSAMS ranged from 41.67-63.84 dB, which averaged a value of 56.22 dB and corresponded to a frequency range from 2-5 kHz.
2) The MSA of the linen fabric measured using the manual FSAMS ranged from 41.32-58.51 dB, which averaged a value of 52.80 dB and corresponded to a frequency range from 1-2.5 kHz.
3) The MSA of the silk fabric measured using the manual FSAMS ranged from 35.54-60.20 dB, which averaged a a value of 49.73 dB and corresponded to a frequency range from 1.5-5 kHz.

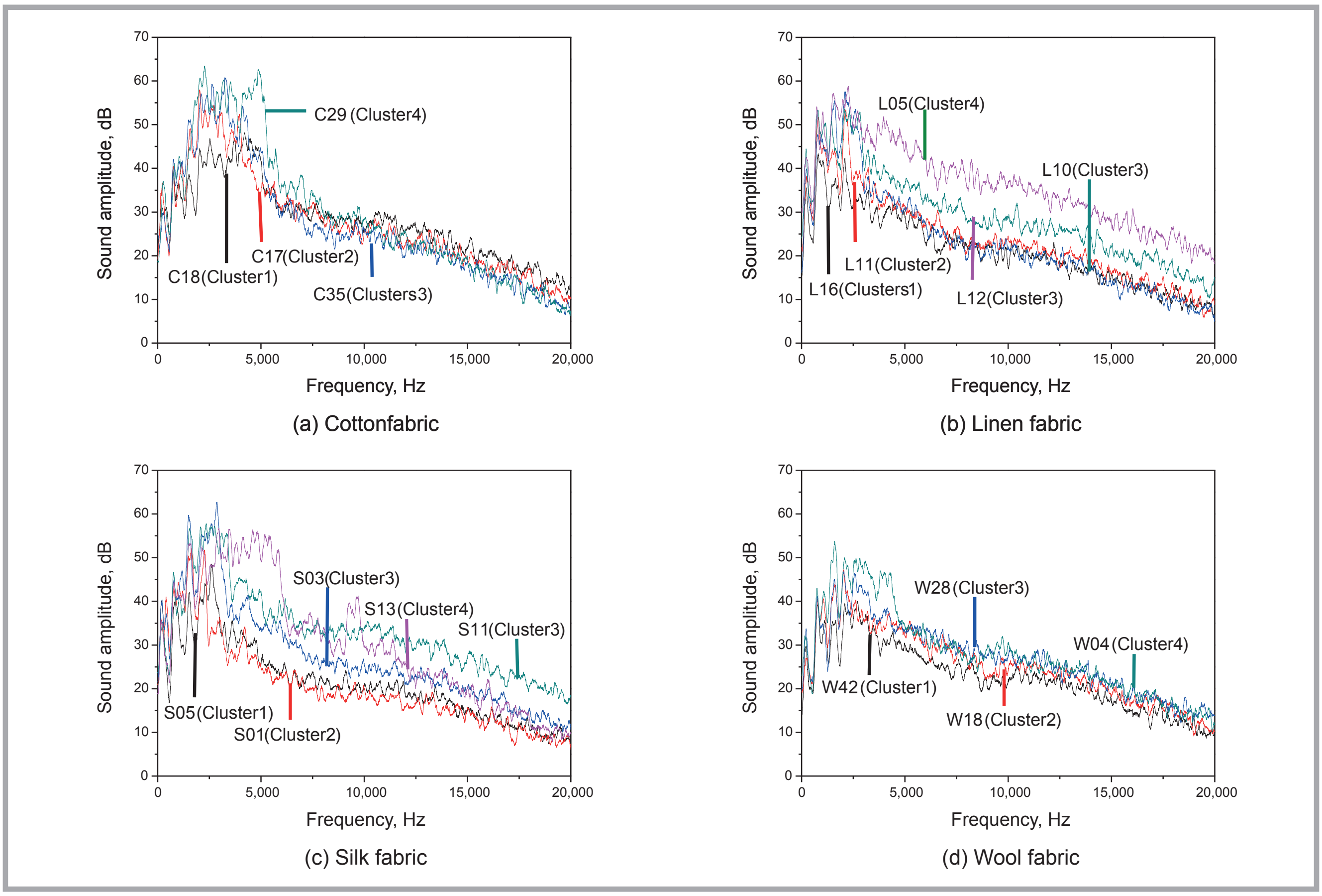

Figure 5. *Cluster spectrums of four natural-fiber woven fabrics by the manual FSAMS system.*

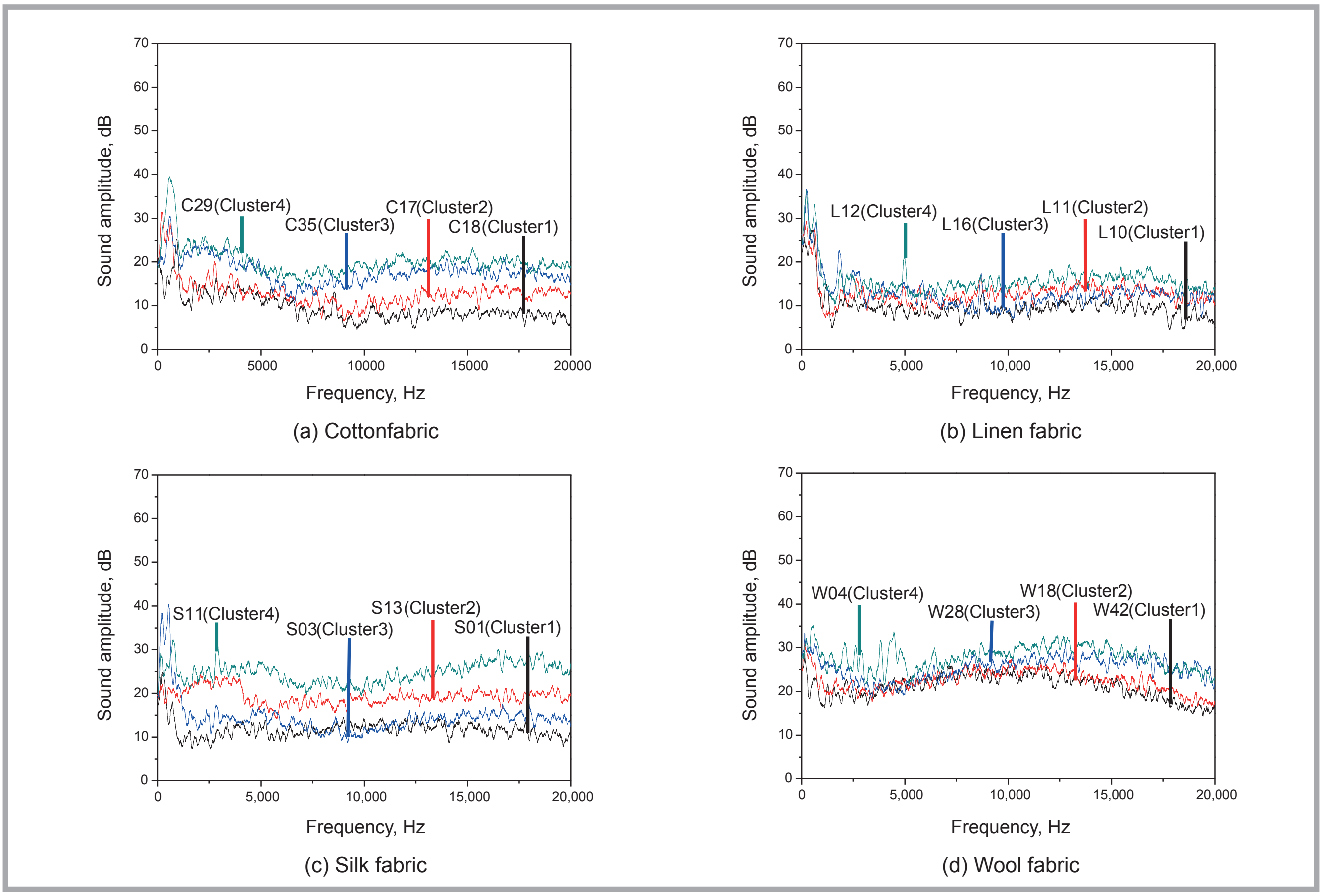

Figure 6. *Cluster spectrums of the four natural-fiber woven fabrics by the automatic FSAMS system.*

4) The MSA of the wool fabric measured using the manual FSAMS ranged from 35.47-57.15 dB, which averaged a value of 45.05 dB and corresponded to a frequency range from 1.3-2.8 kHz.

Figure 6 shows the following:

1) the MSA of the cotton fabric measured using the automatic FSAMS ranged from 21.54-46.53 dB, which averaged a a value of 31.04 dB.
2) The MSA of the linen fabric measured using the automatic FSAMS ranged from 24.06–33.93 dB, which averaged a value of 29.62 dB.
3) The MSA of the silk fabric measured using the automatic FSAMS ranged from 21.12-40.90 dB, which averaged a value of 31.55 dB.
4) The MSA of the wool fabric measured using the automatic FSAMS ranged from 26.19-37.03 dB, which averaged a value of 31.06 dB.

The corresponding frequency ranges of all four clusters were from 200-800 Hz. Regardless of using the manual or automatic FSAMS systems, the cotton, linen, and wool fabrics yielded differences in decibel intensities because of different clusters; but the shapes of their spectrums were similar; the silk fabric not only yielded a difference in decibel intensities but also resulted in comparatively larger differences in the spectrum shapes. Lastly, corresponding spectrums were exported for each cluster of the four different fabrics measured using manual and automatic FSAMS systems to compare the differences in the spectrums of the two equipment systems and the four fabric types.

In ***Figure 7*** and ***Table 6***, the cluster spectrums of the four fabrics measured using the manual FSAMS showed comparatively smaller differences; the spectrums of the four materials and their corresponding characteristics cannot be easily observed. In ***Figure 8*** and ***Table 7***, the cluster spectrums of the four fabrics measured using the automatic FSAMS showed that the spectrums of cotton and linen yielded low decibel values from Clusters 1-4, in which variations were also small and the spectrums were comparatively stable. Among the four fabrics, wool yielded comparatively high decibel values in the spectrums throughout the four clusters, and silk presented comparatively random results and larger variations.

Table 6. *MSAs of the four natural-fiber woven fabrics by the manual FSAMS system and automatic FSAMS system.*

		MSAs (manual FSAMS system)			MSAs (automatic FSAMS system)		
Fabric	Cluster	Min	Max	Mean	Min	Max	Mean
Cotton	Cluster 1	41.67	54.53	47.63	21.54	25.48	23.09
	Cluster 2	53.00	58.00	54.92	22.10	33.68	26.55
	Cluster 3	56.26	63.46	58.79	29.01	38.20	33.43
	Cluster 4	60.16	63.84	61.93	34.35	46.53	41.09
Linen	Cluster 1	41.32	46.88	44.28	26.49	27.81	26.96
	Cluster 2	47.29	53.33	50.88	24.06	31.50	28.73
	Cluster 3	51.28	58.51	54.28	28.10	33.93	31.50
	Cluster 4	56.93	56.94	56.93	27.21	33.57	31.28
Silk	Cluster 1	35.54	46.29	39.13	21.12	31.10	25.30
	Cluster 2	42.67	49.66	47.28	23.55	32.64	30.03
	Cluster 3	53.06	60.20	55.39	29.98	37.96	34.90
	Cluster 4	54.38	55.77	55.08	31.01	40.90	35.95
Wool	Cluster 1	35.47	43.85	39.67	26.19	29.44	28.30
	Cluster 2	39.65	52.65	44.01	26.56	30.98	29.11
	Cluster 3	43.46	57.15	46.79	29.44	34.99	32.15
	Cluster 4	36.57	55.36	49.56	32.58	37.03	34.69

Table 7. *MSAs of four natural-fiber woven fabrics in four clusters by the manual FSAMS system and automatic FSAMS system.*

Cluster	Cluster	MSAs (manual FSAMS system)	MSAs (automatic FSAMS system)
Cluster 1	Cotton	46.8 (C18)	22.72 (C18)
	Linen	41.32 (L16)	26.58 (L10)
	Silk	46.29(S05)	23.67 (S01)
	Wool	38.66 (W42)	26.19 (W42)
Cluster 2	Cotton	54.40 (C17)	29.12 (C17)
	Linen	51.71 (L11)	27.49 (L11)
	Silk	49.66 (S01)	23.55 (S13)
	Wool	44.61 (W18)	29.19 (W18)
Cluster 3	Cotton	59.14 (C35)	29.01 (C35)
	Linen	51.28 (L10)	31.21 (L16)
	Silk	56.13 (S03)	36.59 (S03)
	Wool	44.91 (W28)	30.85 (W28)
Cluster 4	Cotton	61.41 (C29)	38.54 (C29),
	Linen	56.93 (L05)	33.57 (L12)
	Silk	54.38 (S13)	31.01 (S11)
	Wool	51.44 (W04)	34.33 (W04)

Conclusions

1. It was shown that outputs from the manual and automatic FSAMS test equipment systems exhibited significant differences in the T-test and ANOVA analyses.

2. The analysis of data reproducibility showed that friction sound values measured using the automatic FSAMS were more stable and more representative than the manual FSAMS. This is because the manual FSAMS can be affected by human factors and ambient noises, which cause large experimental errors.

3. The spectra obtained using manual and automatic FSAMS showed that the frequencies corresponding to the MSAs measured by the manual FSAMS were from 1 ~ 5 kHz and the average MSAs of test fabrics were from 49.73 ~ 56.22 dB. The frequencies corresponding to the MSAs measured by the automatic FSAMS, were from 200 ~ 800 Hz and the MSAs of test fabrics were from 29.62 ~ 31.55 dB.

4. The cluster spectra of the automatic FSAMS showed that different fabrics yielded various spectrum shapes, in which cotton, linen, and wool generated comparatively stable spectra, whereas the silk fabric presented a comparatively larger variation in the spectrum shapes. The spectra measured from the manual FSAMS yielded

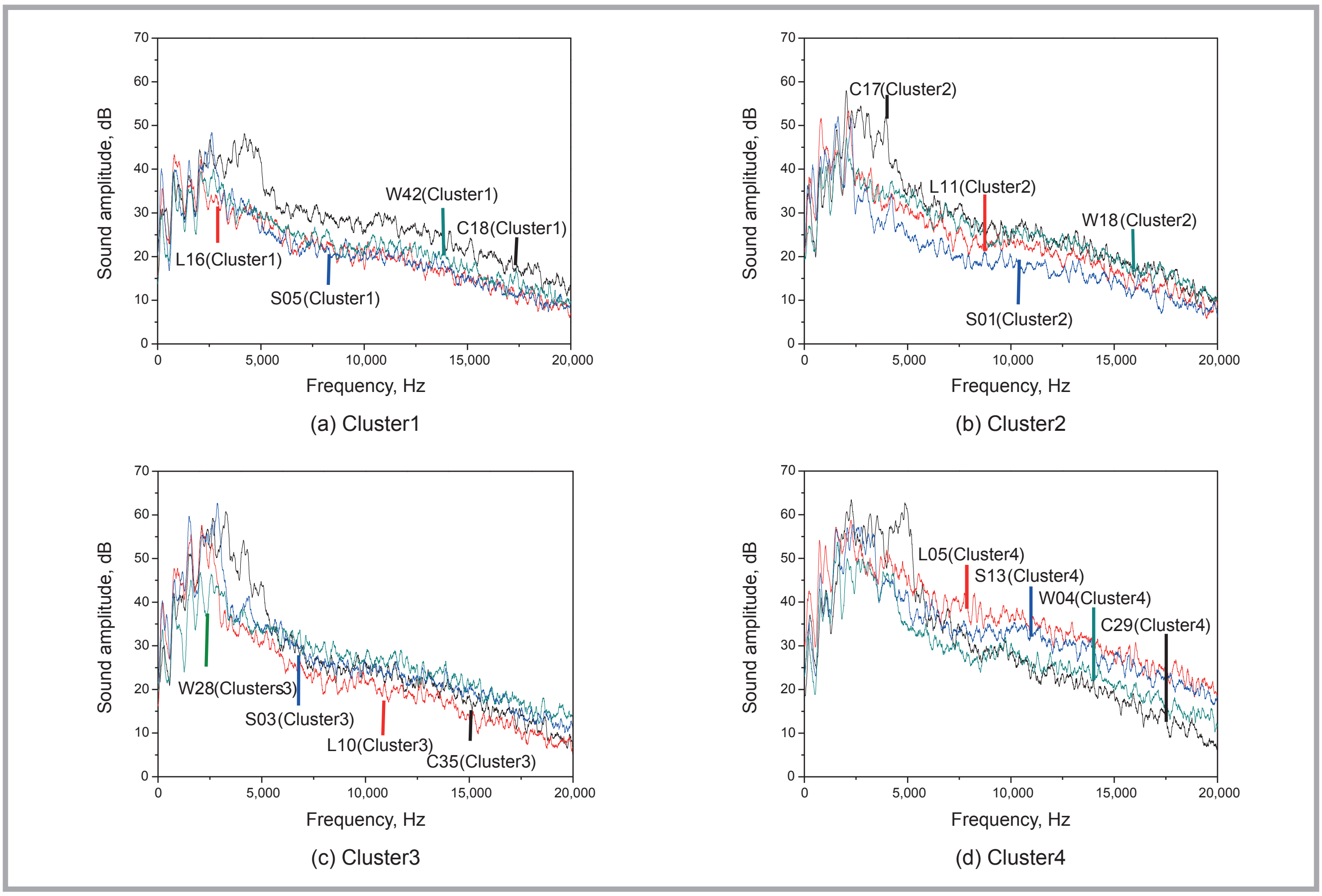

Figure 7. *Cluster spectrums of the four natural-fiber woven fabrics in four clusters by the manual FSAMS system.*

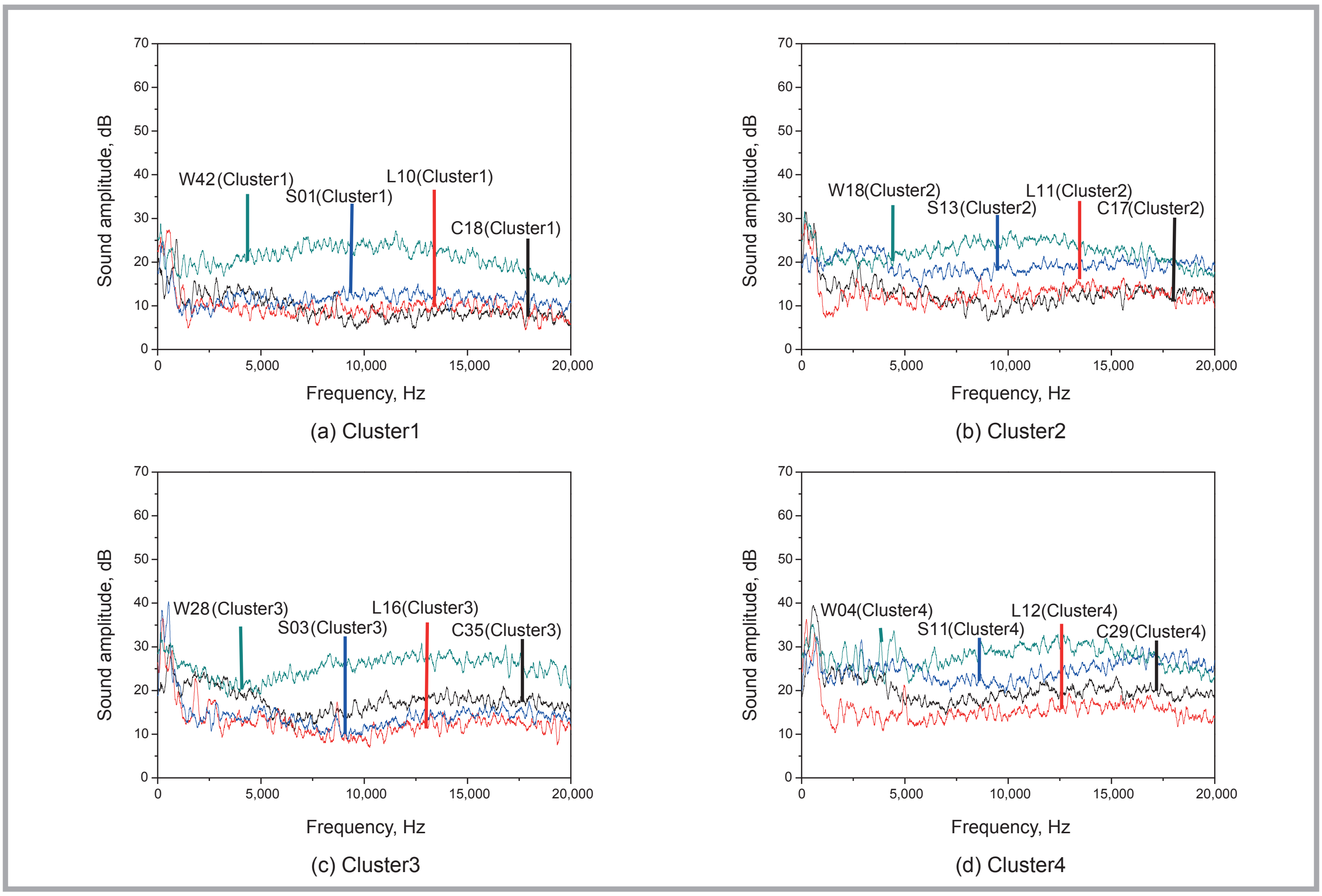

Figure 8. *Cluster spectrums of the four natural-fiber woven fabrics in four clusters by the automatic FSAMS system.*

comparatively smaller differences; the spectra arising from the different materials and their corresponding characteristics cannot be easily observed.

5. In prospective studies, it would be useful to place emphasis on evaluating the correlation between fabric frictional sounds, AR coefficients, and the mechanical properties of fabrics. In addition, stepwise regression would be preferable for selecting and analyzing the mechanical parameters affecting fabric frictional sounds

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