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A Study on the Dynamic Bending Properties of Textile Fabrics

Kim Jongjun
Professor, Dept. of Clothing and Textiles, Ewha Womans University

Abstract

With the advancements in the computer graphics sectors, the visual quality of the virtual clothing implemented by using the 3-dimensional digital clothing software system has been much improved during the past decade. Most of the cloth simulation procedures are complicated due to the multitude of parameters involved in the simulation in order to achieve the appearance of the actual textile fabrics or the movement of the actual clothing as close as possible. Bending properties affect the tactile and visual qualities of the textile fabrics along with the shear and tensile properties. In this study, dynamic bending properties, focused on the movement of the textile fabrics including damping ratio and amplitude, were measured by using a dynamic bending test system.

Key Words : bending, flexural rigidity, stiffness, virtual clothing simulation, damping

I. Introduction

The past decade has seen notable progress in the 3-dimensional clothing simulation software systems, with the advancements in the textile industries and the pioneering studies in the computer graphics sectors.[1,2] The appearances and movements of the plastic-like characters or garments of human figures in the animation movies of the quickening period have transformed to more elegant, fluidic, and realistic looks of the characters in the recent movies based on the state-of-the-art technologies.

Bending property is one of the important factors governing the aesthetics and handle of apparel textiles products. By introducing the fabric properties, including bending, shear, tensile, and others[3,4], the level of realism attained by the 3-dimensional clothing simulation system has been much improved during the last decade.

A 3-dimensional clothing simulation system which employed a 3-D quadrangular mesh founded on a mass-spring system was proposed recently.[5] In the study, the KES(Kawabata Evaluation System) parameters were measured including shear, tensile, and bending, in order to

Corresponding author; Kim Jongjun, Tel. +82-2-3277-3102, Fax. +82-2-363-3078
E-mail: jjkim@ewha.ac.kr

implement the dynamic draping behavior of the selected fabrics.

Numerous achievements have been reported in the computer graphics sectors for the 3-dimensional clothing simulation systems. Volino and Manenat-Thalmann[2] compared the efficiency of integration methods during the clothing simulation process. Oshita and Makinouchi[6] introduced the smoothing method to add rich details on a coarse clothing mesh. In their clothing simulation model, elastic and bending force were introduced as internal cloth forces. The bending force was computed for each edge. Additional forces such as gravity, air velocity and damping forces were also introduced. They suggested the use of wrinkle patterns provided by a designer or pre-computed patterns based on a dynamic simulation in order to attain more refined and plausible wrinkles or creases on the simulated clothing. At the same time, the exact pattern making[7] is of pivotal importance in the apparel manufacturing industry. In the 3-dimensional virtual clothing simulation, the level of precision of the supplied pattern data affect the final output of the simulated clothing products.[8] The realism of clothing depends largely on the fabric creases or wrinkles generated during the simulated wearer's motion or static posture. Choi and Ko's[9] suggestions on the simulations incorporating the 'immediate buckling assumption' produced realistic wrinkles without the instability during the simulation process. With the advancement in the computer graphics sectors and 3-dimensional clothing simulation softwares, the level of requirement for the realism in the software systems is also heightened. As the apparel industries deal with mostly multi-layered fabric designs, it is therefore necessary to simulate the exact behavior of the layers of fabrics. Accurate modeling of bending behavior of the multi-layered fabrics with seams need different approaches in dealing with the measurement of bending. Pabst et al.[10] proposed an instrument capable of measuring the bending behavior of multi-layered fabric with seams. The instrument is based on the principle of the cantilever flexural rigidity tester with several new designs. The new designs include 17 distance measuring sensors, automatic specimen feeding system enabling accurate determination of the fabric specimen. Goldenthal et al.[11] proposed a method to obtain very low strain along the warp and weft direction, taking into consideration the fact that many textiles do not noticeably stretch under their own weight.

The dynamic drape properties of textile fabrics are important parameters in determining the movement and fluidity of the textile materials in active situations of the wearer. Recently, dynamic drape test methods have been employed to evaluate the drape property simulating the movement of the wearer.

In this study, dynamic bending properties, focused on the movement of the textile fabrics due to the external force imposed on the fabrics, are measured by using a dynamic bending test system, which is suggested as a prototype testing device.

II. Theoretical Backgrounds

1. Dynamic Drape Properties

Drape properties of textile fabrics are closely related to the aesthetics of apparels. The dynamic drape properties of textile fabrics are important parameters in determining the movement and fluidity of the textile materials in active situations of the wearer. Static drape evaluation has long been employed to measure the drape coefficient or drape profiles of the textile fabrics. Recently, dynamic drape test methods have been employed to evaluate the drape property simulating the movement of the wearer.

Yang and Matsudaira[12] define the dynamic drape coefficient with swinging motion Dd, which is considered to be similar to the wearer's motion during walking, and also derived a regression equation from the basic mechanical parameters of fabrics. The instrument is comprised of a circular supporting stand of 127 mm diameter with 0-240 rpm rotating capability.

The dynamic drape coefficient, D_d, is defined as "the degree of draping shape change of fabrics at a swinging motion". When the value of D_d is large, the fabric is regarded as being easy to change its draping profile even with delicate external force such as light wind and or swinging motion of the wearer. Matsudaira et al.[13] studied the dynamic and static drape properties of Shingosen polyester fabrics including the peach-faced type and new-worsted type fabrics. The D_d, swinging dynamic drape coefficients, of the peach-faced type fabric was small while that of the new-worsted type fabric was large. On the other hand, there were no significant differences between each group of Shingosen fabrics in the measured number of nodes and the static drape coefficients, D_s. The study results regarding the dynamic drape coefficient and the related parameters would provide a good foundation for the 3d virtual clothing simulation software systems.

2. Viscoelastic Behavior of Textile Materials

The elastic recovery of a fiber or yarn depends on the nature and the fine structure of the polymer comprising the fiber or the yarn structural parameters including fiber length, fiber crimp, friction coefficient, fiber cross-sectional shape, the level of yarn twist, heat setting conditions. The elastic recovery may be analyzed mostly using the stress-strain curve of the materials. The type of recovery is divided to the instantaneous and the delayed recovery type. In the evaluation of textile fiber deformation, it is important to note the amount of permanent deformation.

Static viscoelasticity may be found in the stress relation and creep deformation. Dynamic viscoelasticity refers to the case of repeated excitation, for instance, the case of external excitations such as sinusoidal external excitations imposed to one end of the fixed fibrous specimen.

The viscoelastic properties of textile fibers or yarns may be examined using the dynamic mechanical analysis system. In a uniaxial tensile deformation test, low amplitude of sinusoidal oscillatory strain is imposed to one end of the specimen clamps and the resultant tensile stress is measured at the other end. The viscoelastic property measurement instrument measures the temperature dependence or frequency dependence of the complex modulus (E*) and loss tangent (tan δ) of viscoelastic materials at specific frequencies or temperatures.[14]

Complex dynamic modulus E^*, or complex Young's modulus, is represented as the function of the oscillating stress and strain:

$$E^* = \frac{\sigma^*}{\epsilon^*} = E' + i\,E'' \qquad \text{(eqn. 1)}$$

E' is the storage modulus and E'' is the loss modulus.

The loss tangent : $\tan\delta = E'' / E'$ (eqn. 2)

The lagging between the strain and the stress shows up as hysteresis in the stress-strain relation. Some energy is lost in the hysteresis loop. Purely viscous material will show the strain lag behind the stress of 90 degree angle. Most of the viscoelastic materials show the lag between 0 to less than 90 degree angle. As the value of loss tangent increases, the contribution of the viscosity of the material increases.

The orientation and crystallinity of the fiber specimen have a good amount of influence on the dynamic modulus measurement. The modulus is much greater in the highly oriented materials. Thus, the viscoelasticity is one of the prime factors considering the nonlinear mechanical properties of textile fibers.

3. Bending Properties of Textile Materials

Bending property is one of the important factors governing the aesthetics and handle of apparel textiles products. The tactile properties including the stiffness feel are highly related to the bending properties of the textile materials. In terms of textile fabric processing, extremely low stiffness of a fabric may cause problems in handling during garment manufacture,[15] or unwanted crease generation during dyeing and finishing processes. Bending properties also play an important role in fabric draping together with the shear properties and fabric weight itself.

It has been reported that the frictional constraint couple M_f of textile fabric changes with the bending curvature.[16] Seo et al.[17] studied the deflections of fabrics based on nonlinear bending properties. The nonlinear bending properties of fabrics were measured from the KES bending test. They assumed the bending moment is a function of curvature. They compared the image analysis results of the cantilever beam deflection of fabrics, read as x-y coordinates of the fabric deflection profiles, with the KES bending moment results.

As a constituent factor, the flexural rigidity of the textile fiber is described as follow:

$$\text{flexural rigidity} = \frac{1}{4\pi}\frac{\eta E T^2}{\rho}\times 10^{-5}\ \text{gf·cm}^2$$

(eqn. 3)

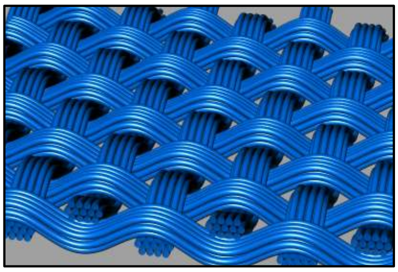
where E : modulus [gf/tex]

ρ : density [g/cm^3]

T: count of filament [tex]

η : shape factor of fiber cross-section

Peirce[2] proposed a flexural rigidity test method based on the measurement of cantilever length of a fabric specimen. In the experiment, one edge of the fabric strip specimen is fixed on a platform and deflected under its own weight as a cantilever. Cantilever test has widely been used due to the simplicity and the relatively good correlation to the subjective evaluations. Grosberg and Swani[18] reported that frictional forces are important in terms of the flexural behavior by increasing its resistance to bending and impeding its recovery from deformations, suggesting a model of fabric bending with an initial friction restraint M_o that must be first overcome before the subsequent linear bending moment-curvature relation. The initial friction restraint is explained by the frictional resistance to the initial bending deformation at the warp-filling yarn intersections of woven fabric. <Figure 1>



<Figure 1> Perspective view of a woven fabric model showing intersections of warp and filling yarns, friction-causing element during initial bending of a fabric (plain weave structure of multi-filament yarns)

Clapp et al.[19] proposed an indirect measurement method to find the relationship between moment and curvature using a cantilever beam test. Cartesian coordinate values(x-y), along the curved profile of the lengthwise cross-section fabric specimen, were collected.

Based on the cantilever bending test principle, the bending rigidity of a fabric[20,21] is calculated as follow:

$B = W \cdot c^3 \cdot 9.807 \times 10^{-6}$ [μN·m] (eqn. 4)
where W : fabric weight per unit area [g/m^2]
c : L/2 [mm]

Lahey[22] proposed a model of bending hysteresis in order to reproduce the fabric pure bending moment-curvature curves measured by using the KES (Kawabata Evaluation System). When a material's stress-strain behavior follows a linear elastic mode, a spring element represents the model behavior. The mechanical behavior of polymeric fiber is viscoelastic, comprising the characteristics of elasticity and viscosity. The model for the polymeric fiber is then a combination of a spring and a viscose dashpot. For bending of a textile fabric, both friction and damper elements were introduced in the bending hysteresis mode.[23]

The author divided the KES bending curve into three phases:1) Bending curve from a stopped position to a maximum positive curvature, K+, 2) Bending to a maximum negative curvature, K-, and 3) Returning to the initial stopped position of zero curvature. The rotational movement of the fabric clamp needs an initial acceleration stage from the stopped position to the instrumentally predefined constant curvature rate of 0.5cm^{-1}, constant rate stage, and deceleration to rest.

Fabric bending moment is measured using a rectangular effective fabric specimen size of 1x20cm when the KES is used. The specimen is bent for a range of curvature radius between 2.5 and -2.5cm^{-1}. This bending moment measurement is conducted at a constant rate of 0.5cm^{-1}.

Also studies on the textile fabric finishing have been reported regarding the hand, finishing conditions, and the effect on the appearance including simulated drape or simulated clothing.[24-27]

When the apparel fabric is in motion due to the wearer's movement, the fabric may be accelerated or decelerated with the motion. Human eyes are very sensitive to the behavior of the fabrics. Griffiths and Kulke[28] studied on the relationships between the tactile attributes that were assessed with a sensory evaluation method and the fabric mechanical properties measured using the F.A.S.T. (Fabric Assurance by Simple Testing). It was concluded that, in some cases, it is possible to identify the fabric type based on the observation of its shape and motion.

In this study, the pattern of the fabric movement including the amplitude of fabric oscillation, and the damping of the fabric is analyzed.

For modeling simplicity, damping model used in this study is the mass-spring-damper system.

$$M_f(\kappa)(t) = (f_1 - f_2) sign(\dot{\kappa}(t)) + sign(k(0)) \left[e^{-\frac{s(t)}{\epsilon_f}} f_2 - e^{-\frac{s(t)}{\epsilon_f \eta}} f_1 \right]$$
(eqn. 5)

where $s(t)$ is the total curvature that the fabric specimen has been deflected at time t.

Under-damping case is considered in this experiment. In this case, the system oscillates at the natural damped frequency ω_d.

The general solution[29] will be:

$$x(t) = (e^{-\zeta\omega_0 t})(A\cos(\omega_d t) + B\sin(\omega_d t))$$

(eqn. 6)

The natural damped frequency of the system is:

$$\omega_d = \omega_0\sqrt{1-\zeta^2} \; . \qquad \text{(eqn. 7)}$$

The value of ζ, damping ratio, can be calculated from the logarithm of the ratio of consecutive amplitudes.

The logarithmic decrement, δ, is calculated as:

$$\delta = \ln\left(\frac{x_1}{x_2}\right) . \qquad \text{(eqn. 8)}$$

The damping ratio, ζ, then, can be calculated as follow:

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} \qquad \text{(eqn. 9)}$$

The parameters obtained from the dynamic measurement may contribute to the function of the 3-dimensional virtual clothing simulation systems in the future based on the possible database of fabric property measurements.

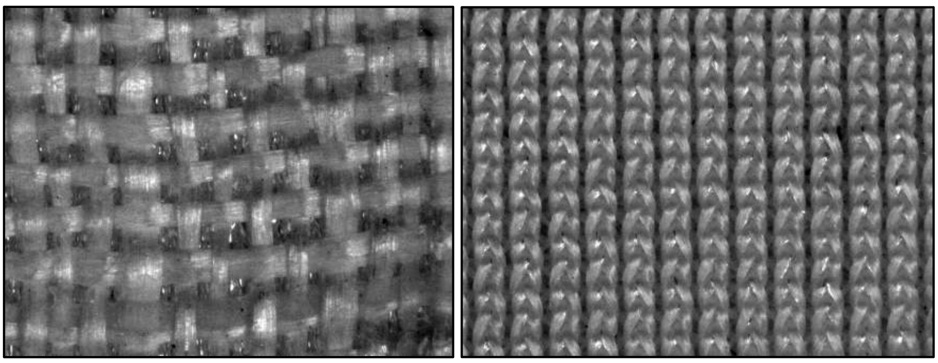
III. Experiments

1. Fabric Specimens

In order to measure the dynamic bending moment of textile fabrics, two distinctive specimens were selected. Fabrics made of hemp are well-known for the traditional summer wear material in Korea due partially to the unique stiffness and the coolness. The velour specimen is chosen for its pliability, drape property, and elasticity since this particular velour specimen comprises elastomeric yarn and polyester filament yarn.<Table 1> <Figure 2>

<Table 1> List of fabric specimens

Fabric Code	Construction	Type	Fiber Composition
H	Woven Fabric	Plain Weave	Warp: Hemp 100%
			Filling: Hemp 100%
V	Knitted Fabric	Pile Knit(Velour)	Polyester 97%
			Polyurethane 3%



<Figure 2> Photomicrographs of fabric specimens, H and V(back)

2. Dynamic Bending Test System

A bending test system is devised to measure the dynamic bending behavior of textile fabric specimens. The dynamic bending tester system measures the change of bending force during the specimen's movement.<Figure 3>

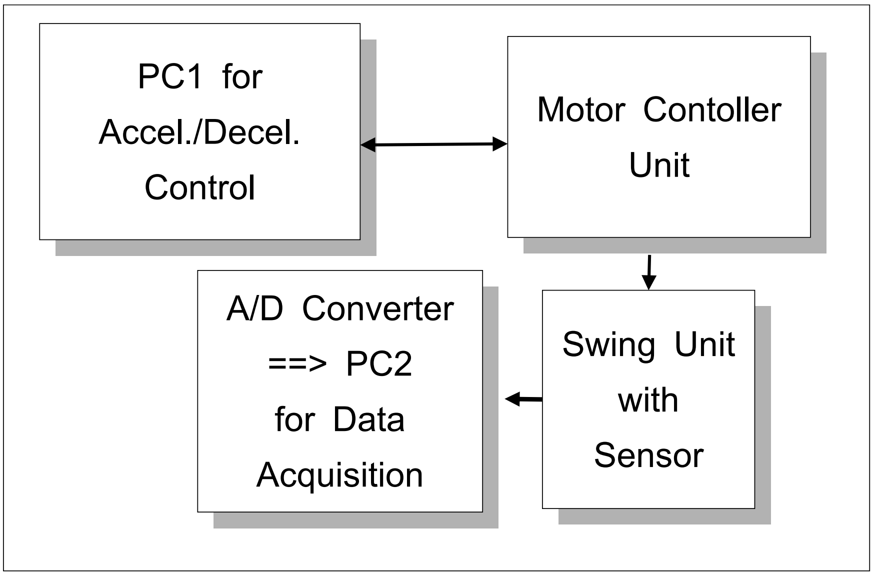
The specimen movement is controlled by a motorized swing unit<Figure 4>, which is controlled by a motor controller unit interfaced to a computer, PC-1. The acceleration, deceleration and stop motion is controlled accurately by the motion controller system. The top portion of the fabric specimen<Figure 4: A> is clamped between the fabric clamp faces connected to a torque sensor<Figure 4: B>. The analog signal from the torque sensor is fed to the pre-amplifier connected to the analog-digital converter. The digitized signal stream is delivered to another computer, PC-2, at a rate of 100Hz, for data acquisition and processing. Since the level of measured bending force is relatively low, the signal should be amplified ensuring electrical noise as low as possible.

The fabric specimen is mounted between the clamp faces vertically on the Dynamic Bending Test System.

Ⅳ. Results and Discussion

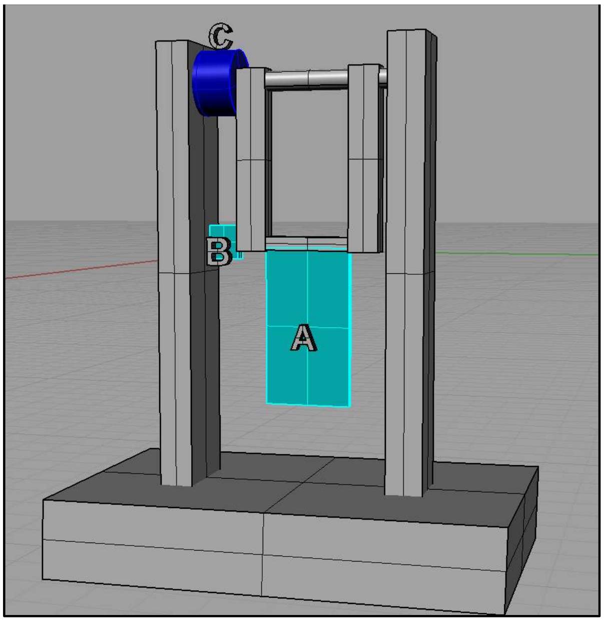
When the fabric specimen oscillates, the torque sensor measures the bending force signal. The signal is then calculated as bending moment per specimen width. The bending moment of the fabric specimen decreases as the oscillation amplitude decreases due to the air drag, hysteresis, and other parameters.

<Figure 5> shows the change of bending moment of the fabric specimen H during the oscillatory movement immediately after the release of the specimen from the angle of 52 degrees. Immediately after the release, the bending moment reaches to a peak value of 0.9861gf·cm/cm. After 6 seconds have passed, the oscillatory amplitude is hard to be recognized on the chart. Also, the movement of the fabric oscillation

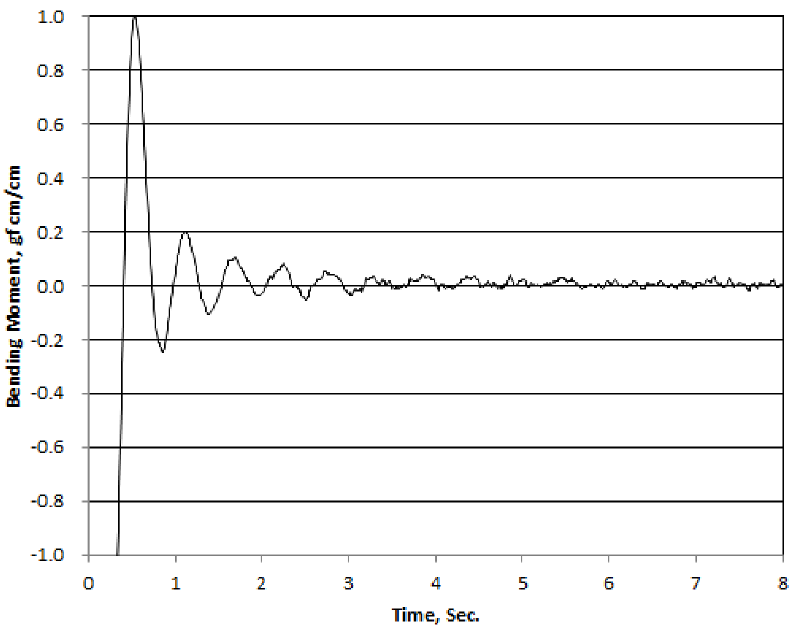


<Figure 3> Dynamic bending test system

is hardly recognizable based on visual observation.

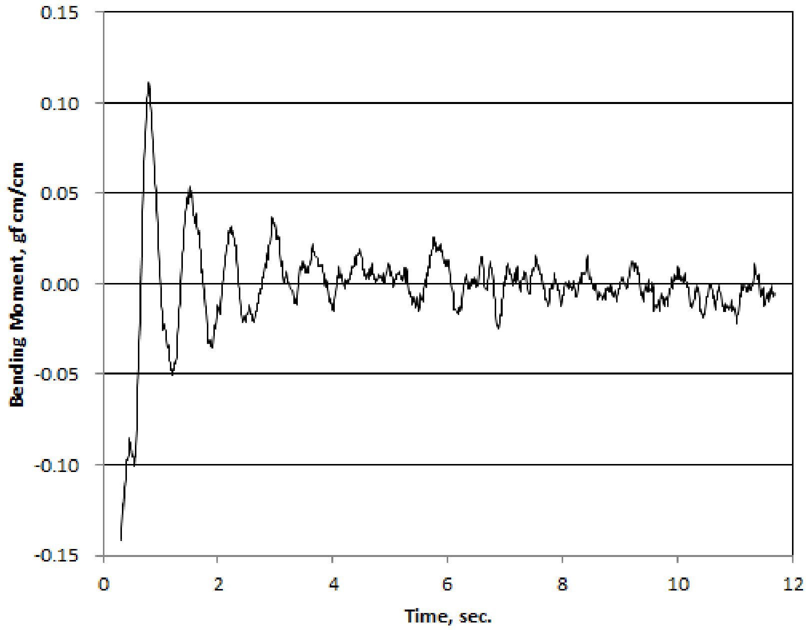


<Figure 4> Dynamic bending test system : swing unit, A: fabric specimen, B: torque sensor, C: motor



<Figure 5> Dynamic bending moment with time, fabric H (hemp)

<Figure 6> shows the change of bending moment of the fabric specimen V during the oscillatory movement. The span of the bending moment axis is almost 1/8 of that shown in <Figure 5>, since the stiffness of the specimen V is much lower than that of the specimen H. Thus, the peak value of the bending moment (peak 1) is 0.1110 gf·cm/cm. It is noteworthy that the oscillating movement of the specimen V is visually recognizable compared to that of the specimen H.



<Figure 6> Dynamic bending moment with time, fabric V (velour)

<Table 2> Dynamic bending properties of fabric specimens, peak time and peak moment

Peak No.	H		V	
	Time of peak, sec.	Peak moment, gf·cm/cm	Time of peak, sec.	Peak moment, gf·cm/cm
peak1	0.52	0.9861	0.79	0.1110
peak2	1.08	0.1770	1.51	0.0538
peak3	1.64	0.0956	2.19	0.0293
peak4	2.19	0.0604	2.93	0.0338
peak5	2.67	0.0220	3.64	0.0191
peak6	3.23	0.0235	4.42	0.0161
peak1.5	0.82	−0.2143	1.19	−0.0475
peak2.5	1.34	−0.0690	1.51	−0.0328
peak3.5	1.91	−0.0224	1.83	−0.0166
peak4.5	2.46	−0.0330	2.19	−0.0068
peak5.5	2.97	−0.0209	2.41	−0.0098

As shown in <Table 2>, the bending moment of the fabric specimen H(Hemp) reaches the maximum moment value of 0.9861gf·cm/cm(peak 1) at peak time 0.52sec. The second positive peak at 1.08sec., the bending moment peak(peak 2) decreases to 0.1770gf·cm/cm. The average period is 0.54sec. The measured values of peak moments decrease exponentially.

The regression equation of the exponential curve of the positive peaks, based on the experiment, is:

$$y = 2.5\,e^{-1.682x},$$

where y is the bending moment of the peak, and x is time of peak.<Figure 7>

The bending moment of the fabric specimen V(Velour) reaches the maximum bending moment value of 0.111gf·cm/cm, which is about 11% of that of the fabric specimen H. Since the specimen H is much stiffer than V to the touch, the peak moment of V is lower than that of H.

However, the amount of displacement of the specimen V seems to be larger than that of H based on visual observation. This is largely due to the relation between the bending moment and the bending curvature parameters. Therefore, it would be worthwhile to measure the displacement along with the bending moment measurement during the dynamic bending test.

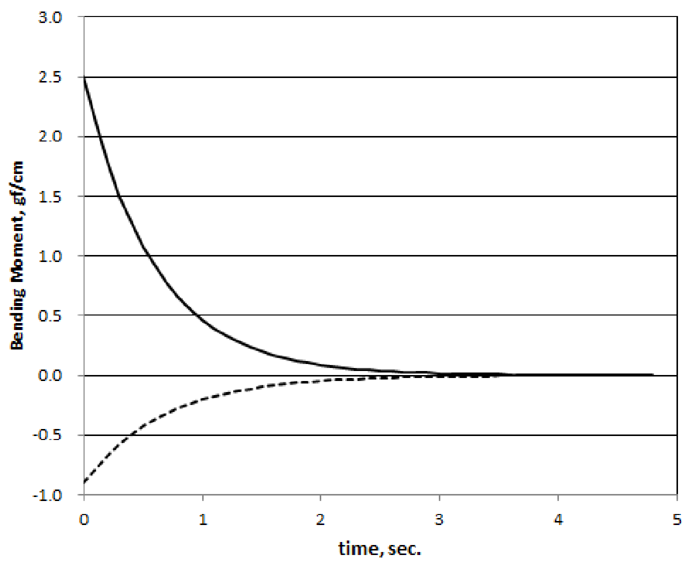
The regression equation of the exponential curve of the positive peaks of the specimen V, based on the experiment, is:

$$y = 0.205\,e^{-0.651x},$$

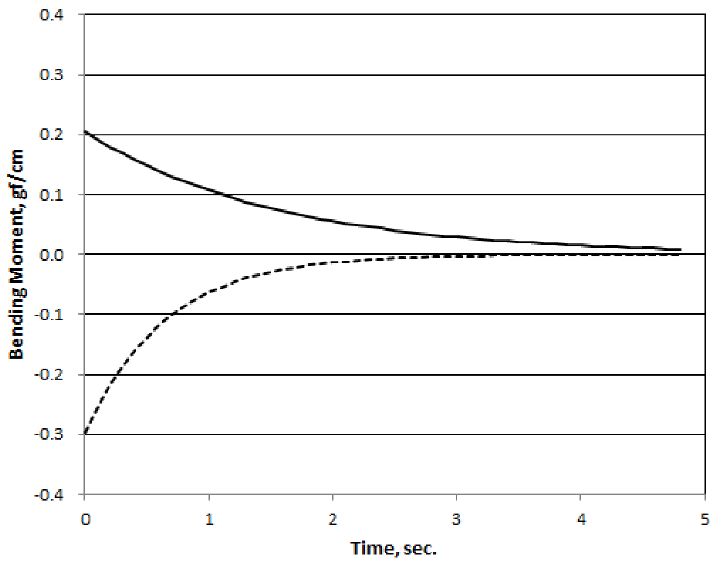
where y is the bending moment of the peak, and x is time of peak. <Figure 8>

As shown in this <Figure 8>, the oscillation of the fabric V bending moment lasts longer than that of the fabric H.

<Table 3> shows the calculated damping parameters of fabric specimens. The logarithmic decrement of the specimen H is 1.369 while that of the specimen V is lower(0.882). The dampingratio



<Figure 7> Damping chart (regression lines calculated from the peak values of the acquired digital signals of the torque sensor), sample: H(hemp), warp direction



<Figure 8> Damping chart (regression lines calculated from the peak values of the acquired digital signals of the torque sensor), sample: V(velour), course direction

<Table 3> Calculated Damping Parameters of Fabric Specimens

Damping parameter	H	V	Remark
Logarithmic decrement, δ	1.369	0.882	Peak1/Peak2
Damping ratio, ζ	0.213	0.139	

calculation results show that the damping ratio of the specimen H is 0.213, while that of the specimen V is 0.139, indicating that the damping of the H(Hemp) is much higher than that of the V(Velour). The results of the measurement of the damping ratio together with other damping parameters would provide some simulation parameters for the 3-dimensional virtual digital clothing systems in the future.

V. Conclusion

The textile and clothing industries have shown deep interests in the application of 3-dimensional virtual clothing simulation systems, which are being developed with interdisciplinary efforts of the textile and clothing industries and the computer graphics sectors. The simulation systems do not only provide realistic and elegant appearances of clothing, but also try to faithfully reflect the mechanical and physical properties of textile fabrics. The accuracy and realism of the simulated clothing and textile fabrics depend largely on the correct parameters supplied into the simulation system.

These days, by using the objective textile fabric characterization system such as the KES, most of the measured mechanical and physical properties of the fabric may be utilized for the improvement of the realistic clothing simulation.

Main attention of this study is focused on the dynamic bending properties of the textile fabrics, including the maximum bending force, damping ratio, and the individual peak time of the oscillating fabric specimens by using the devised system.

1. In order to measure the parameters, a dynamic bending test system employing a torque sensor, A/D converter, and motor unit for swing motion is prepared with a few software products to acquire data streams. The measured parameters seem to differentiate the dynamic fabric characteristics reasonably.

2. The logarithmic decrement of the specimen H is 1.369 while that of the specimen V is lower(0.882). The damping ratio calculation results show that the damping ratio of the specimen H is 0.213, while that of the specimen V is 0.139, indicating that the damping of the H(Hemp) is much higher than that of the V(Velour).

3. The results of the measurement of the damping ratio together with other damping parameters would provide some simulation parameters necessary for the 3-dimensional digital clothing simulation systems in the future.

4. The dynamic displacement measurement of the fabrics together with the bending moment measurement using a torque sensor, shown in this study, would help in-depth interpretation of the dynamic behavior of the fabrics.

Reference

1) K. J. Choi, H. S. Ko(2002), "Stable but responsive cloth", *ACM Transactions on Graphics (Proceedings SIGGRAPH 2002), 21(3)*, pp.81-97.
2) P. Volino, N. Magnenat-Thalmann, (2001), "Comparing efficiency of integration methods for cloth simulation", *CGI '01 Proceedings of the International Conference on Computer Graphics*, pp.265-274.
3) F. T. Peirce(1930), "The 'handle' of cloth as a measurable quality", *J. Textile Inst., 21(9)*, pp.377-416.
4) S. Kawabata(1980), *The standardization and analysis of hand evaluation, 2nd ed.*, The Textile Machinery Society of Japan, Osaka, Japan, pp.65-88.
5) F. Ji, R. Li, Y. Qiu(2006), "Three-dimensional garment simulations based on a mass-spring system", *Textile Res. J., 76(1)*, pp.12-17.
6) M. Oshita, A. Makinouchi(2001), "Real-time cloth simulation with sparse particles and curved faces", *Proc. of Computer Animation 2001 14th Conference*, Seoul, Korea, pp.220-227.
7) Shin J. H., Sohn H. S.(2009), "Comparative study of productive pattern and educational pattern of tailored-collar", *Journal of Fashion Business, 13(5)*, pp.37-44.
8) Chang H. K., Sohn H. S.(2011), "Classification of upper body types for the establishment of a size standard for Chinese women", *Journal of Fashion Business, 15(1)*, pp.103-114.
9) K. J. Choi, H. S. Ko(2005), "Research problems in clothing simulation", *Computer-Aided Design, 37*, pp.585-591.
10) S. Pabst, et al.(2008), "Seams and bending in cloth simulation", *Workshop in Virtual Reality Interactions and Physical Simulation VRIPHYS*, pp.31-38.
11) R. Goldenthal, et al.(2007), "Efficient simulation of inextensible cloth", *ACM Transactions on Graphics, 26(3),* pp.1-4.
12) M. Yang, M. Matsudaira(2001), “Measurement

of drape coefficient of fabrics and description of hanging shapes of fabrics, part 6: evaluation of dynamic drape behavior of fabrics in swinging motion", J*ournal of Textile Machinery Society of Japan, 54(3),* T57-T64.
13) M. Matsudaira, et al.(2002), "Polyester 'Shingosen' fabrics characterized by dynamic drape coefficient with swinging motion", *Textile Res. J., 72(5)*, pp.410-416.
14) M. Takayanagi(1963), "Viscoelastic properties of crystalline polymers," *Mem. Fac. Eng. Kyushu Univ., 23(1),* pp.2-12.
15) N. Pan, S. H. Zeronian, H. S. Ryu(1993), "An alternative approach to the objective measurement of fabrics", *Textile Res. J., 63(1)*, pp.33-43.
16) F. Shi, J. Hu, T. Yu(2000), "Modelling the creasing properties of woven fabrics", *Textile Res. J., 70(3)*, pp.247-255.
17) Seo J. I., Yu W. R., Chung K. S., Kang, T. J.(2000), "Deflection of fabrics based on nonlinear bending properties", *J. Kor. Fiber Soc.*, *37(5)*, pp.286-292.
18) P. Grosberg, N. M. Swani(1966), "The mechanical properties of woven fabric - part IV: The determination of the bending rigidity and frictional restraint in woven fabrics", *Textile Res. J., 36(4)*, pp.338-345.
19) T. G. Clapp, et al.(1990), "Indirect measurement of the moment-curvature relationship for fabrics", *Textile Res. J.*, *60(9),* pp.525-533.
20) K. Ancutiene, E. Strazdiene, A. Nesterova (2010), "The relationship between fabrics bending rigidity parameters defined by KES-F and FAST equipment", *Materials Science, 16(4)*, pp.1392-1320.
21) P. Szablewski, W. Kobza(2003), "Numerical analysis of Peirce's cantilever test for the bending rigidity of textiles", *Fibres & Textiles in Eastern Europe, 11(4*), pp.54-57.
22) T. J. Lahey(2002), "Modelling hysteresis in the bending of fabrics", University of Waterloo master of applied science thesis, pp.31-33.
23) J. Lindberg, B. Behre, B. Dahlberg(1961), "Mechanical properties of textile fabrics - part III: shearing and buckling of various commercial fabrics", *Textile Res. J., 31(2)*, pp.99-122.
24) Park Jiyang, Jeon Dongwon, Kim Sinhee (2008), "Physical property and virtual sewing image of Lyocell treated with epichlorohydrin for the fibrillation control", *Journal of Fashion Business 12(6)*, pp.46-60.
25) Kim Kyungsun, Jeon Dongwon, Kim Jongjun(2009), "Physical properties and virtual cloth images of cotton fabrics treated with chitosan, 1,2,3,4-butanetetracarboxylic acid and citric acid", *Journal of Fashion Business, 13(1),* pp.102-114.
26) Lee Jungmin, Kim Jongjun, Jeon Dongwon (2008), "A study on the appearance characteristics of selected fabrics for ecology trends", *Journal of Fashion Business, 12(4),* pp.131-142.
27) Cho Jongihm., Kim Jongjun, Jeon Dongwon (2007), "Hand and physical properties of mercerized cotton fabric using KES", *Journal of Fashion Business, 11(1)*, pp.125-135.
28) P. Griffths, T. Kulke(2002), "Clothing movement —visual sensory evaluation and its correlation to fabric properties", *Journal of Sensory Studies, 17(3)*, pp.229-255.
29) A. Papoulis(1984), *Probability, Random Variables, and Stochastic Processes(2nd ed.)*, New York: McGraw-Hill, pp.525-527.

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