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Short Communications

Theoretical and experimental methods of dynamic clothing pressure performance

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A dynamic pressure measuring system has been developed in this study. This system can be used for static pressure measuring, real-time dynamic pressure measuring and pressure fatigue analysis. A 3D geometric model on fabric deformation as well as mechanical behavior has been developed, which can be used for simulating the fabric elongation during dynamic pressing, and to deduce relationship between the press depth and fabric elongation. The process parameters of measuring system have been systematically estimated and analyzed. The range of press depth fixed for dynamic pressure measurement is found to be 58-115 mm, which responds to the fabric elongation from 10% to 40%. The press velocity at 100 mm/min is considered as the optional one for dynamic pressure measurement. Five repeated test cycles can be satisfied to assess the dynamic pressure fatigue performance quickly.

Keywords: Cotton fabric, Dynamic pressure, Geometrical model, Spandex fabric

A variety of elastic fabrics are used to make compression products for operational application such as tight-fitting garments or girdles, medical stockings, and medical bandages for wounds, venous ulceration, deep vein thrombosis and burns[1]. ‘Compression product’ is a kind of product which applies pressure to specific areas of human body. In daily practice, it is well known that the behavior of a compression products can significantly differ from others, the pressure changes due to the three dimensional deformation of compression fabric, and relates to its physical and mechanical properties, such as tensile, shearing, and bending properties[2-6]. The pressure is divided into static and dynamic. The static pressure is defined as the pressure exerted on the special area of human body when the compression products have no additional deformation, while the dynamic pressure is defined as the pressure exerted during the 3D deformation of compression products.

For pressure to be effective in compression products, a pressure measuring system is essential to test the amount of pressure actually imposed. In European Committee for Standardization[7], the pressure values of a compression garment are measured indirectly in a laboratory setting. The tensile tension of the compression garment is measured under semi-static conditions. Laplace’s law, which relates pressure, tensile tension and curvature radius, was used to calculate the pressure of the compression garment. Lately, a variety of developed measuring techniques can be used to determine pressure performance directly under each device, however, no one system has been established or identified as the only or the best way to measure these pressures. Nishimatsu *et al*.[8] measured pressure of socks using an elastic optical fibre. Moreover, Fan and Chan[9] reported the development of a basic system to measure clothing pressure based on a soft manikin. This system is limited to the assessment of static pressure distribution without consideration of dynamic contact mechanics. And several other studies have been conducted on designing new pressure measuring system based on air-pack type pressure sensor, flexiforce pressure sensor or matrix of tensometric sensors[10-13]. However, they do not provide information on the dynamic behavior of compression products. In practice, pressure changes of the compression products during body motion are more important[14]. So, the dynamic pressure behavior should be investigated under the processing of fabric 3D deformation.

In our previously research[15], a pressure measuring system was developed. In addition, an improved pressure measuring device with more pressure sensors distributed on the surface of hemisphere was designed and equipped on this system. Therefore, static pressure, real-time dynamic pressure and fatigue analysis can be researched via this system. In this investigation, a geometric model of the fabric 3D deformations has been developed and its mechanical behavior is studied, which contribute to the responding relationship between press depth and fabric elongation. The process parameters of the measuring system have also been systematically estimated and analyzed.

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Experimental

Materials

Two kinds of knitted fabric (Sample 1 and Sample 2) were purchased commercially as test specimens and their properties are listed in Table 1. Each sample was cut into circular form with radius of 35 cm, and was conditioned in a standard atmosphere for 24 h prior to the formal testing.

Clothing Pressure Measuring System

In this research, we developed a system for measuring static and dynamic clothing pressure during the fabric 3D deformation, composed of three components, namely pressure measuring device, displacement driving device, and data acquisition device. In addition, an improved pressure measuring device was designed with more pressure sensors distributed on the surface of hemisphere[15]. The sensors are distributed on the surface of hemisphere (located at site 1, site 2 and site 3), sensing the static pressure and dynamic pressure during the hemisphere downward-upward motion. Figure 1 shows the photograph of the clothing pressure measuring system.

Measuring Procedure

To evaluate the dynamic pressure behavior of compression products, first put fabric sample on the holding device, turn on the computer-driven system software for equipment self-testing, standard initialization, and input measuring parameters including velocity of vertical motion, press depth (here, press depth is defined as the distance of hemisphere vertically motion), and test cycles. Finally start the clothing pressure measurement. The driving device keeps the hemisphere moving in vertical direction according to the predetermined parameters. Pressure sensors detect pressure signal, transmitted to computer via signal amplifier, data acquisition and processing module, and finally the signal was recorded and displayed.

Table 1—Basic description of elastic fabrics

Sample	Fibre content	Course density wales/5cm	Wale density courses/5cm	Thickness mm	Weight g/m^2
1	32^{s}cotton/model50/ 50+30D spandex	81.7	127.0	0.50	198
2	40^{s}cotton/model50/ 50+30D spandex	90.0	128.7	0.62	220

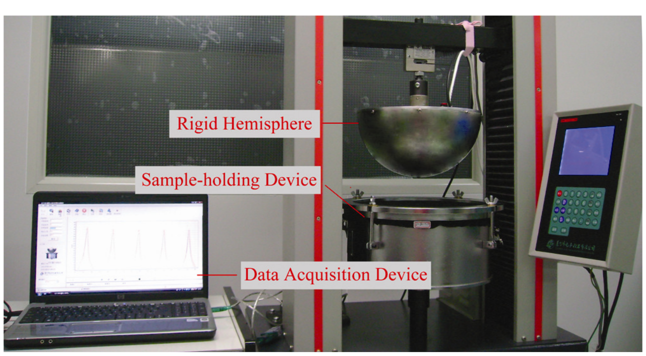

Fig. 1—Photograph of clothing pressure measuring system

Theory

Geometrical Model

Figure 2 shows the geometrical relation among press depth, diameters of fabric sample and hemisphere.

Assume that the radius of the hemisphere is r (mm), the radius of fabric sample is R (mm), where $R>r$ (according to the technique parameter of the system, R=136 mm, r=126 mm), and the original diameter of fabric sample is $D_0=2R$. Assume that the time when the sensor at site 1 contacts with fabric is 0, the hemisphere vertically moves downward at velocity of v mm/min over a period of time, so the elongation of fabric sample can be described as:

$$\varepsilon = \frac{D_1 - D_0}{D_0} \cdot 100\% \quad \ldots(1)$$

$$h = vt \quad \ldots(2)$$

$$D_1 = 2l + 2\pi r \cdot \frac{2\psi}{2\pi} \quad \ldots(3)$$

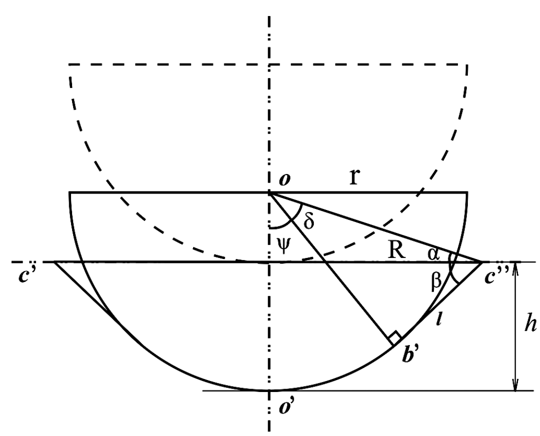

Fig. 2—Geometrical relation among press depth, diameters of fabric sample and hemisphere

$$l = \sqrt{R^2 + (r - vt)^2 - r^2} \quad \ldots(4)$$

$$\psi = \arctan\left(\frac{r}{\sqrt{R^2 + (r - vt)^2 - r^2}}\right) - \arctan\left(\frac{r - vt}{R}\right) \quad \ldots(5)$$

where h is the hemisphere distance (mm), defined here as "press depth"; D_1, the size of the fabric sample at time t; l, the length of b'- c''; α, an angle of oc''- $c'c''$; β, an angle of $c'c''$- $o'c''$; δ, an angle of oc''- ob'; and ψ, an angle of ob'- oo'.

The parameters described in Eqs (4) and (5) can be obtained quantitatively by geometry relation among press depth, the diameters of fabric sample and the hemisphere (Fig. 2).

Substituting Eqs (4) and (5) into Eq (3), we have

$$D_1 = 2\sqrt{R^2 + (r - vt)^2 - r^2} + 2\pi r \cdot \frac{2 \cdot \left(\arctan\left(\frac{r}{\sqrt{R^2 + (r - vt)^2 - r^2}}\right) - \arctan\left(\frac{r - vt}{R}\right)\right)}{2 \cdot \pi} \quad \ldots(6)$$

The elongation values increase with the hemisphere downward motion to the maximal press depth, and then decrease with the hemisphere upward motion.

Mechanical Analysis

During hemisphere downward-upward motion, the sample deforms in three dimensions due to internal stresses including tension, shearing and bending. These internal stresses cause the contact pressure on its interface, which is named as "clothing pressure". The physico-mechanical properties of fabric show significant effect on its pressure performance, especially for tension, shearing and bending.

In wearing, mechanical interaction occurs at the contact surface between body and garments. The fabric contacting area increases while it changes from natural state to 3D deformed state. Figure 3 shows the physical process of before and after 3D deformation. Assumed that the plane projection of deformed fabric is equal to the geometric projection of its natural state. In processing, the circle *ob* deforms to the spherical cap *o'b'*, and the circle *bc* deforms to the curved surface *b'c'*. Each element must be elongated since the fabric area is increasing. In region *o'b'*, the fabric keeps in contact with hemisphere surface, which is subject to multi-stresses in multi-direction, the stresses are varied at different regions, and the sensors at site1, site2, and site 3 measure the clothing pressure respectively.

Results and Discussion

Press Depth

According to the elasticity, fabric can be divided into three categories including high-elastic, medial-elastic and low-elastic fabric. The high-elastic fabric has advantages in stretch and resilience, the range of elasticity is from 30% to 50%, and the tensile resilience is from 94% to 95%; the medial-elastic fabric is known as comfortable stretching fabric, elasticity is from 20% to 30% and tensile resilience is from 95% to 98%. The low-elastic fabric generally has lowest elasticity which is below 20%, and the tensile resilience is above 98%.

People engaged in various activities in life show that the skin is elongated in horizontal and vertical directions at the range of 20-50%. Table 2 shows the skin elongation in various activities [16].

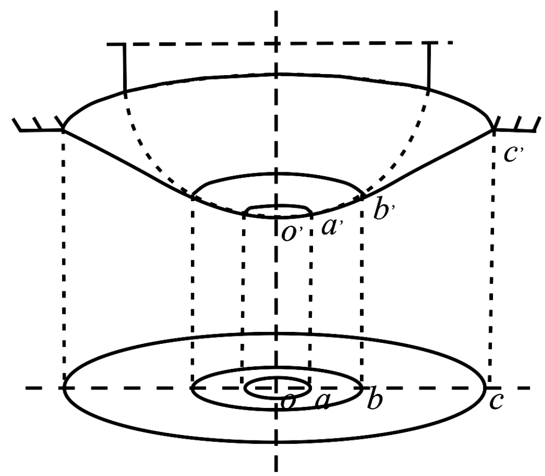

Fig. 3—Fabric state of before and after 3D deformation

Table 2—Skin elongation in various activities

Body	Activity	Skin elongation, % Horizontal direction		Vertical direction	
		Men	Woman	Man	Woman
Knee	Sit down	21	19	41	43
	Bending	29	28	49	52
Elbow	Bending	24	25	50	51
Hip	Sit down(complete)	20	15	27	27
	Sit down(partly)	42	35	39	40
	Squat(complete)	21	17	35	34
	Squat(partly)	41	37	45	35

In the processing of dynamic pressure measurement, the press depth is one of most important parameters which respond to the elongation of fabric. In wearing, mostly elastic compression garments keep the elongation 5-50%. Based on the above analysis and the test range of the system, the elongation is controlled within 10-40%, to test the dynamic clothing pressure at step elongation of 10, 20, 25, 30, 40%.

According to Eqs (1)-(6), the press depth values are 58, 81, 90, 99, and 115 mm for fabric elongation of 10, 20, 25, 30, 40% respectively.

Press Velocity

The dynamic pressure magnitudes are different at varied press velocity even for the same sample and at the same elongation. Figure 4 shows the dynamic pressure values for sample 1 and sample 2 at 50, 100, 150, and 200mm/min velocity respectively.

In the five times test cycles, the change in dynamic pressure magnitudes is found relatively stable at 50 mm/min and 100 mm/min velocities. The dynamic pressure value is less at lower press velocity since it has more time interval for stress relaxation. In dynamic pressure test, the downward velocity of 100 mm/min is employed for the comparison with static pressure. Table 3 shows the dynamic pressure value on site 2 and site 3 at varied press velocity.

Test Cycles

Figure 5 shows the decay of dynamic pressure with the increased test cycle of 15 times at 30% elongation. Table 4 illustrates the loss of dynamic pressure after 5 cycles (signed as P_d5) and 15 cycles (signed as P_d15) at the elongation of 25% and 40% respectively. It is found that the relative loss in dynamic pressure after 5 cycles is more than 80% as compared to that after 15 cycles. It is deducted that the decay tendency of dynamic pressure after five cycles is subtle, hence five test cycles can be used to assess the fatigue of dynamic pressure performance simply and fast.

The loss of dynamic pressure and relative loss of dynamic pressure are defined in the following way:

$$P1n = \frac{P_1 - P_n}{P_1} \times 100$$

$$Pr1n = \frac{P1n_1}{P1n_2} \times 100$$

where P_{1n} is the loss of dynamic pressure at n cycle; P_1, the dynamic pressure at 1st cycle; P_n, the dynamic pressure at n cycle; P_{r1n}, the relatively loss of dynamic pressure; P_{1n_1} the loss of dynamic pressure at n_1 cycle; and P_{1n_2}, the loss of dynamic pressure at n_2 cycle.

Pre-tension

A certain pre-tension should be applied on the sample before testing to make sure the initial contact with the hemisphere surface. The value of pre-tension is decided by the weight of samples.

The dynamic pressure measuring system is an effective tool to be used for static pressure measurement exerted by compression products on the surface of hemisphere, for dynamic pressure measurement in real-time, and for pressure fatigue measurement in both static and dynamic state.

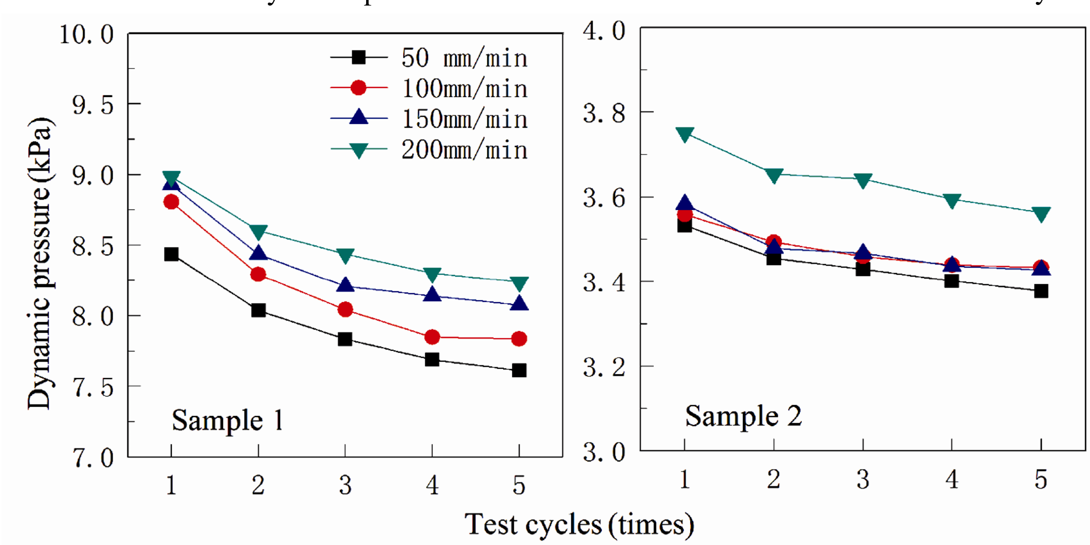

Fig. 4—Dynamic pressure value at varied press velocity

Table 3—Dynamic pressure value (kPa) on site 2 and site 3 at varied press velocity

Sample	Sensor location	Press velocity mm/min	Dynamic pressure, kPa 1[a]	2[a]	3[a]	4[a]	5[a]
1	Site 2	50	7.18	6.84	6.67	6.55	6.48
		100	7.57	7.11	6.96	6.77	6.74
		150	7.57	7.25	7.10	6.98	6.94
		200	7.81	7.39	7.20	7.17	7.08
	Site 3	50	7.02	6.71	6.58	6.47	6.41
		100	7.30	7.02	6.86	6.72	6.69
		150	7.57	7.12	7.00	6.79	6.78
		200	7.76	7.36	7.15	7.06	7.05
2	Site 2	50	2.99	2.94	2.90	2.89	2.88
		100	3.01	2.99	2.99	2.89	2.93
		150	3.05	2.98	2.97	2.94	2.93
		200	3.16	3.10	3.06	3.04	3.03
	Site 3	50	2.90	2.89	2.84	2.82	2.62
		100	2.96	2.90	2.85	2.84	2.82
		150	2.98	2.93	2.92	2.89	2.87
		200	3.00	2.94	2.93	2.89	2.89

[a]No. of test.

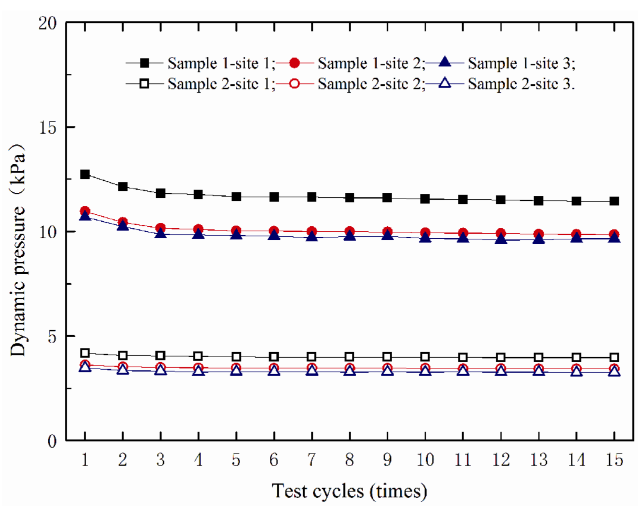

Fig. 5—Decay of dynamic pressure value

Table 4-Relative loss of dynamic pressure

Sample	Elongation %	Sensor location	P_d5 %	P_d15 %	P_d5/P_d15 %
1	25	Site-1	6.13	7.10	86.35
		Site-2	5.82	6.90	84.39
		Site-3	5.32	6.48	82.09
2		Site-1	4.41	5.47	80.77
		Site-2	4.72	5.75	82.11
		Site-3	4.89	6.04	80.94
1	40	Site-1	7.70	9.57	80.40
		Site-2	8.15	10.09	80.76
		Site-3	7.08	8.84	80.09
2		Site-1	8.68	10.62	81.74
		Site-2	7.62	9.37	81.34
		Site-3	15.39	19.12	80.51

The process parameters of the measuring system have been systematically estimated and analyzed. The range of press depth fixed for dynamic pressure measurement is 58-115 mm, which responds to the fabric elongation from 10% to 40%. The press velocity at 100 mm/min is considered as the optional one for dynamic pressure measurement. Five repeated test cycles can be satisfied to assess the dynamic pressure fatigue performance quickly. Finally, the pre-tension is determined by the fabric weight.

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