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SMOOTHNESS AND ROUGHNESS: CHARACTERISTICS OF FABRIC-TO-FABRIC SELF-FRICTION PROPERTIES

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ABSTRACT

Smoothness and roughness of fabric materials are important fabric tactile properties for engineering design of many textile products including medical textiles, hygiene and healthcare products, sportswear, underwear, lingerie and other consumer products having special requirements in sensitive surface tactile properties. They are assessed by human fingers and hands in subjective evaluations to form personal perceptions of the fabrics, and they are usually characterised by using the friction coefficient and surface roughness profile during human skin (or artificial human skin/finger/probes) sliding against fabric surfaces in haptic science.

In this paper, the friction coefficient and its spectrum during a fabric surface sliding against the fabric surface itself in a fabric self-friction process are used to characterise the fabric smoothness and roughness. The dynamic friction coefficients and its frequency analysis of its variations of three different fabric materials are assessed against their surface morphological profile. The application of such characteristics of fabric-to-fabric frictional properties in the engineering design of fabric surface structures and their uses in the objective evaluation of fabric hand and discrimination of fabric are also discussed.

Keywords: Smoothness, roughness, fabric-to-fabric friction, coefficient of friction, frequency analysis, LUFHES.

INTRODUCTION

Fabric roughness and smoothness have different meanings in physics. Physically, any surface is generally composed of three components, form, waviness, and roughness, in accordance with wavelength or frequency of surface particles. They are corresponding to the low, medium and in local relative height differences respectively (Militky & Bajzik, 2004). The term roughness refers to height differences of high frequency range of variations on the surface of an object, and it is frequently measured using a profilomete and quantified by the deviations in the direction of the normal vector of a real surface from its ideal form (Whitehouse, 2012) and characterised by roughness heights and roughness width.

Similarly, fabric smoothness (or fabric slipperiness) refers to the fabric surface resistance to a sliding tangential force applied, it is measured by using either static/dynamic fabric coefficient of friction or friction force applied onto the fabric. The magnitude of the friction force is usually more or less proportional to the normal contact force perpendicular to the fabric surface and might also vary with the speed of movement.

Tactual perception of fabric roughness and smoothness

Tactual perceptions of fabric smoothness and roughness are the sensations of two different fabric surface properties. Human sensation of hand touch on a fabric is perceived in the conscious mind through four sensory mechanoreceptors in the skin, namely Meissner corpuscles (FA I), Pacinian corpuscles (FA II), Merkel cell neurite complexes (SA1), and Ruffini end-organs (SA2). The electrical signals produced from the physical deformation (e.g., indentation and stretch) of the soft and flexible skin in the hand caused by mechanical energy applied (e.g., intensity of contact force and speed of motion) (Gardner and Esther P, 2010) is detected to provide information to the brain about the size, shape, form, weight, pressure, motion, vibration and hand posture of objects. These information received by human brain allow us to perceive whether objects appear hard or soft in form, smooth or rough in texture, heavy or light in weight, and whether these sensations produce pain or pleasure in human mind (Johnson and Hsiao, 1992).

Fabric roughness is a multidimensional sensation related to the surface texture, i.e., the dimensions and spatial variations of surface particles/protrudes. It is determined by different physical parameters such as amplitude of the surface profile (Miyaoka, Mano & Ohka,1999), spacing of the surface features (Taylor & Lederman, 1975) and friction between skin and surface (Tiest, 2010), coefficient of friction (Ekman et al,1965), fingertip force and average rate of change of the tangential touching force (Smith et al, 2002).

Roughness perception varies depending on whether the touch evaluation is carried out statically or dynamically. Usually a rough surface produces an uneven pressure distribution on the skin when it is touched statically, and generates vibrations when stroked dynamically (Tiest, 2010). Katz (1925) found that the vibration sense was much more important than pressure sensation for roughness perception. More precisely, it was found in duplex theory (Hollins & Risner, 2000) that the perceived roughness is more readily related to dynamic vibrations on finger skin for fine surface (particles smaller than 100um) while the perceived roughness is more readily related to the particle spatial dimensions for coarse surface (particle size larger than 100 um). This means that either static or dynamic evaluation method is sufficient for discriminating in perception the coarser surface textures having particle sizes greater than 100 um, and that dynamic evaluation method is necessary for discriminating the perception of fine surface textures having particle sizes smaller than 100um. This is attributed to the capability of Pacinian receptors which rendered less sensitive through adaptation with a 100 Hz-300Hz vibration. For finer textures having spatial period less than 200 um), perceived roughness is associated with the amplitude of the vibrations (Hollins & Bensmaïa, 2007).

The perception of roughness and fabric surface textures are correlated based on the ‘‘duplex model of tactile roughness perception’’ (Hollins et al, 1998, Hollins & Risner, 2000). These works distinguish between the perception of fine textures (spatial period is smaller than 100 mm), highlighted by vibrations, and the coarse ones (spatial period is bigger than 200 mm), characterized by a “single spatial intensive code”, mediated by SA I afferents (Hollins et al, 2000).

Employing the methods of combining finger friction measurements with sensory evaluation, Childs and Henson (2007) found that both the sliding friction coefficient and the roughness (peak separation) could partially be related to the perceived feelings of smoothness and roughness. Liu et al (2008) found that both measured surface roughness and friction of different car interior materials could be correlated with the touch-feel perception of “rough” and “slippery” respectively.

In contrary to the fabric roughness as a surface texture property, fabric smoothness is related to fabric surface slipperiness as a frictional property**Error! Bookmark not defined.**. In perception, fabric smoothness is perceived in human mind as a sensation of the resistance to the sliding movement of human skin surface (e.g. a hand or a finger) over a fabric surface. It is found that the relative movement between the two surfaces is essential for obtaining perception of slipperiness (Grierson & Carnahan, 2006). It is found that subjective perception of slipperiness is highly correlation (correlation coefficient of 0.85) to the coefficients of friction of a number of smooth surfaces (Smith & Scott,1996), the discrimination threshold for slipperiness perception were found ranging between 18% and 27% for coefficients of friction between 0.8 and 0.2 (Provancher & Sylvester, 2009). However, friction is an unclearly defined interaction between two surfaces and confusing conclusions are frequently reported due to the fact that roughness perception, rather than slipperiness, is frequently links with frictions properties (Ekman et al,1965). In a research of touch feel of the surface some rigid materials, while roughness perception is highly correlated with the particle sizes, the perceived feel of slipperiness may not be dominated by the friction term. Interestingly, it is also noted that people is able to determine slipperiness statically (Grierson & Carnahan, 2006) when they perform an action to pick up the object (Johansson & Westling, 1984; Cadoret & Smith,1996).

Both of fabric smoothness and roughness are frequently evaluated subjectively by human evaluators, objectively by measuring surface friction properties in haptic devices, and by combining these two methods together (Liu et al, 2008; Childs and Henson, 2007; Chen et al, 2009) when stroking finger (Derler, 2007; Darden and Schwartz, 2009) or a forearm (Gerhardt et al, 2008; Gerhardt et al, 2009) over the fabric surface. However, the measurement of friction effect varies with different methods and can be affected by many factors such as humidity, normal force and speed of movement. It was found that measured friction coefficients between the fingertip and fabrics were not correlated well with the tactile descriptors using by human evaluators in some researches.

The coefficient of friction of objects including fabrics are affected by the surface roughness. Studies have shown that the amplitude of probe surface roughness has a dominant influence on the coefficient of friction between dry fingertip skin and surfaces of smaller roughness (e.g., Ra =0.03 –11.5 um , Rz = 0.05–45 um or Rq = 0.004–2 um) (Masen, 2011; Hendriks & Franklin , 2010); the smaller the amplitude of the probe surface roughness, the higher the coefficient of friction (Masen, 2011; Hendriks & Franklin, 2010; Skedung et al, 2010; Derler et al, 2009). For example, friction coefficients of dry finger skin against a glass of smaller roughness (Rz = 0.05 um) is 2.18 ± 1.09 (range: 0.39–5), whereas friction coefficients on a rough glass surface (Rz = 45 um) is about 0.53 ± 0.22 (0.03–1.42) (Derler et al, 2009), the differences can be as large as a factor 5–10 times at low Ra roughness values less than 1 um (Hendriks and Franklin, 2010). Such differences

have also been observed in the surface having relative fine textures such as papers (in comparison with uncoated fabrics), it was found that coated (smoother) papers shows higher friction coefficients than uncoated (rougher) papers, and that both roughness and finger friction are related to perceived coarseness, and perceived coarseness increases with the increase of rough texture (Skedung et al, 2011).
In contrary, the coefficient of friction increases with the increase of surface roughness for very rough surfaces (Rq = 90 um) (Tomlinson et al, 2009), this is attributed to the effect of friction ridges and ploughing (Derler et al, 2009; Tomlinson et al, 2009).

The friction theory of Moore for elastomers (Moore, 1972)) predicts that the friction coefficient of compliant materials on rough surfaces increases with the surface roughness amplitude. This theory may therefore be applicable to both the places where there are interactions between surface asperities and skin ridges (on the fingers, palm or feet) and the situations where skin in contact with rough surfaces (Ra=3–10 um) (Hendriks & Franklin, 2010). Textiles are considered as soft materials with rough surfaces and have complex material behaviour (Pan, et al, 2007). Skin–fabric friction depends on the textile microstructures such as fibre materials, yarn design/morphology, fabric construction, surface structure, hairiness and finishing (Gerhardt, 2009; Gerhardt, 2008; Comaish & Bottoms,1971; Zhang & Mak, 1999). It was found that there were considerable differences in friction between fabrics made of natural (wool, cotton) and synthetic (polyamide) yarns. Fine loops or crimps of natural fibres might increase frictional resistance to reciprocating motions, leading to greater coefficient of friction and energy dissipation per unit sliding distance (Gerhardt, 2008).

In recent years, the influences of the vibrations induced by frictions between the human skin and the fabric surface on the discrimination of roughness and smoothness perceptions have attracted a lot of attention. When the vibrations generated by frictions between the human skin and the fabric surface in the process of a human finger sliding over a fabric surface, the static and dynamic stress state of the skin are transduced into electrical impulses to activate the four sensory mechanoreceptors located in the skin to allow the brain to perceive tactile information about the fabric surface roughness and smoothness. It is noticed that friction induced vibration to finger skin is one of the key parameters for the perception of fabric roughness. There are two different mechanisms of fabric roughness perception in relation to both roughness wavelength and vibration spectra identified: when the wavelength of the surface roughness is smaller or comparable to that of the fingerprint one, the fabric surface roughness is perceived as a result of the vibrations induced by the finger sliding. When roughness wavelength is much larger than that of the fingerprint one, it is perceived as a quasi-static pressure distribution on the fingertip surface (Fagiani, 2011).

As a summary of about discussions, the perception of fabric smoothness can be determined by fabric dynamic coefficient of friction and is heavily affected by fabric surface roughness or texture amplitude; and the perception of fabric roughness is determined by amplitude of the surface profile and spacing of the surface features, and is affected by the vibration induced by friction with human fingers. That is, the perception of fabric roughness and smoothness affect each other in the complex subjective evaluation process. However, the sensitivity, humidity contents, physical profile and friction properties of human fingers are hugely different from individuals, the perception of fabric roughness and smoothness from subjective assessment is bound to vary widely. In addition, using friction between fabric and hard metal probes might never simulate the real friction-vibration interactions between flexible fabric and viscoelastic human fingers. Therefore, for the purpose of objectively evaluate the fabric smoothness and roughness, it is desirable to develop a method for measuring fabric friction-vibration properties to mimic finger-fabric friction-vibration interactions.

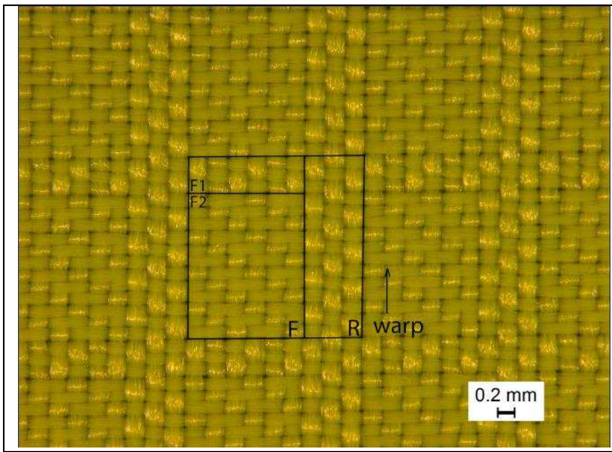
It is known that fabric-to-fabric self-friction is usually a friction of two surfaces having a mixture of rough and fine textures, and the two surfaces are identical and made of flexible polymer fibres. The fabric-to-fabric self-friction will produce detectable vibrations but such properties is currently hardly studied, their characteristics of the friction and vibration processes are still not clear. Therefore, it is a method of great potential to be developed as an objective methods for objectively evaluating fabric roughness and smoothness.

In this paper, the characteristics of the fabric-to-fabric self-friction properties of a thin rip-stop fabric are measured in Leeds University Fabric Handle Evaluation System (LUFHES) (Mao & Taylor, 2012). Its fabric smoothness from coefficient of friction and roughness from vibration induced by friction are compared with fabric roughness obtained from Kawabata Evaluation System.

MATERIALS AND EXPERIMENTAL METHODS

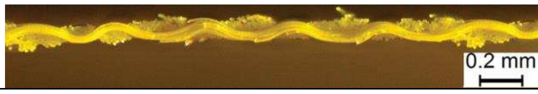
FABRIC MATERIALS

A ripstop woven fabric consisting of low twisted, continuous filament yarns is studied. Its surface structure and cross-sections in ward direction are shown in Figure 1. A unit structure of this ripstop fabric is marked there in a rectangle in Figure 1.



(a) Ripstop fabric surface structure

(b) Cross-section of R area in warp direction



(c) Cross-section of F area in warp direction

Figure 1 Ripstop fabric structure

There are two areas along warp direction in the unit area, ripstop strip (R) and flat strip (F). Ripstop strip (R) contains 3 warp yarns and 15 weft yarns. Each warp yarn in R area contains 5 loops, the warp yarn in one loop has a 2/1 weave structure. Flat strip (F) contains two loops in weft direction, each loop has three warp yarns. F area contains two structures in warp direction, shown as F1 and F2 in Figure 1. F1 contains 3 weft yarns and F2 contains 12 weft yarns. F1 forms the ripstop strip along weft direction. In the F1 area warp yarn has a 2/1 weave structure, which is the same with the ripstop (R) strip. F2 area contains 4 loops in the warp direction, warp yarn in each loop has a 1/2 weave structure.

FABRIC-TO-FABRIC SELF-FRICTION TEST IN LUFHES

The LUFHES friction test unit shown in Figure 1 contains two parts, the surface of upper sample holder is covered by a strip of fabric, and is wrapped by a fabric cylinder made from a piece of identical fabric having longer fabric length, the lower end of the fabric cylinder is fixed onto the lower sample holder during the LUFHS friction test process. A elastic band of known fabric properties and length is employed to provide pressure onto the fabric cylinder on the upper sample holder. During LUFHES friction test, the upper sample holder inside the fabric cylinder is moved upwards at a speed of 1mm/s for 20mm and produced a relative movement in relation to the fabric cylinder to produce fabric-to-fabric friction. The fabric coefficient of friction is obtained from the drag force of upper sample holder and the normal pressure force from the elastic band.

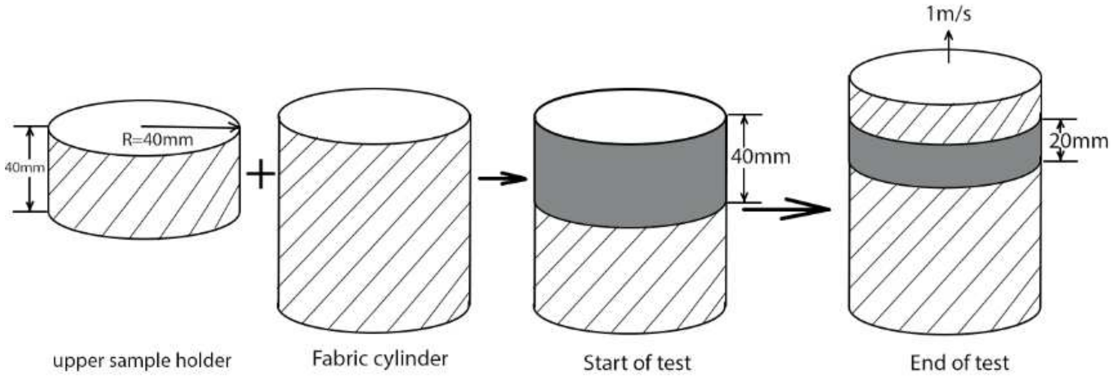


Figure 2 Model of LUFHES friction test

KES-F SURFACE TEST PROCESS

In the KES-F roughness test, as shown in Figure 3, a single wire sensor touches fabric with a constant normal forces, 10g. Fabric moves at a speed of 1mm/s and relative movement take place between fabric and sensor. The vertical movements of contactor caused by the fluctuations on fabric surface are detected by the sensor and recorded for the analysis of roughness. The process of KES-F roughness test contains two rounds. Fabric moves forwards for 30mm in the first round, and then moves backwards to the start point in the second round. Therefore, two groups of data are obtained of the same fabric area in one test.

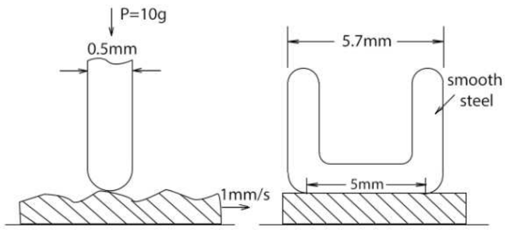
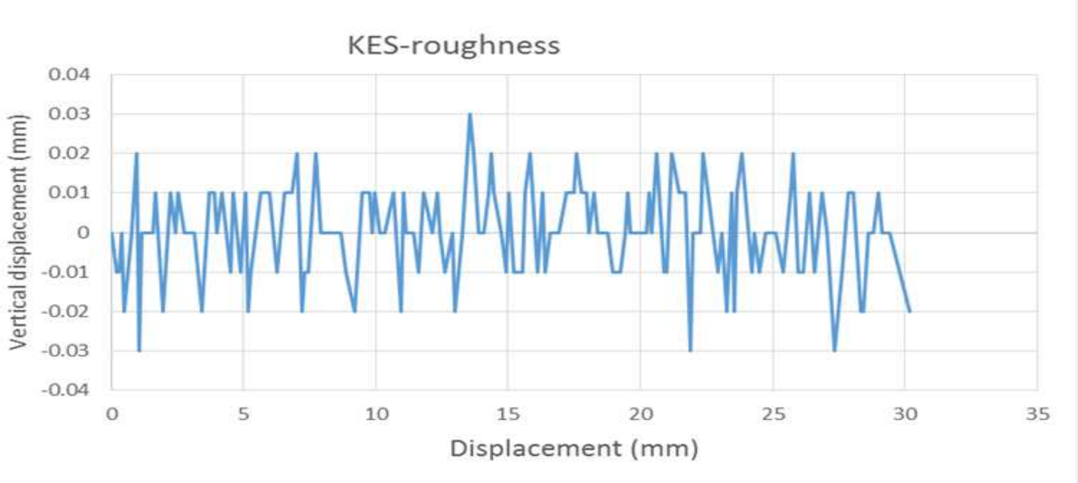


Figure 3 Sensors used in KES-F to test fabric surface properties: Roughness test probe

RESULTS

Roughness from KES test

The roughness results of round 2 test from KES test and its FFT analysis are shown in Figure 4 below.



(a)

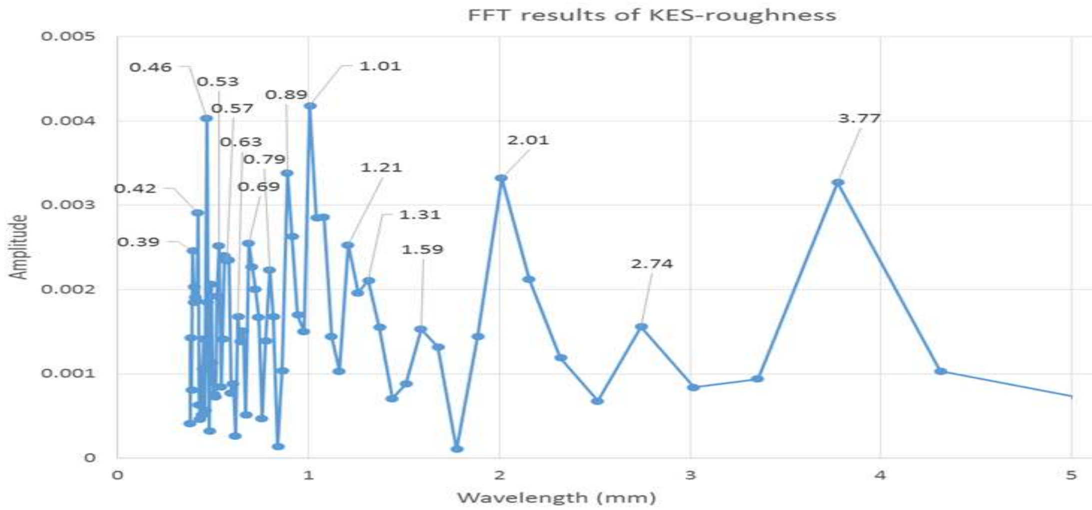
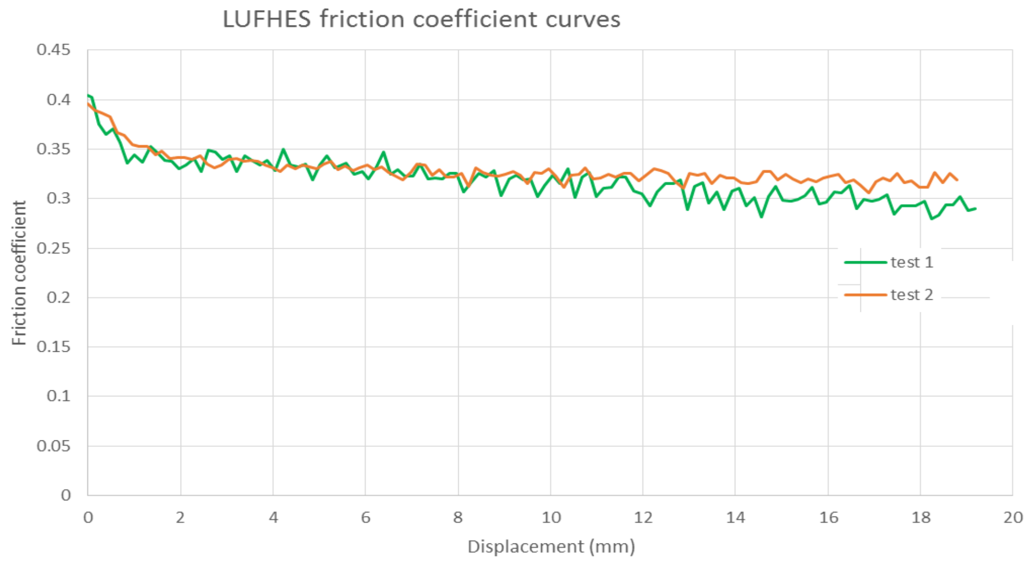


Figure 4 KES-F roughness test results with wavelengths less than 5mm. (a) Round 2 roughness (b) FFT analysis of round 2



(a)

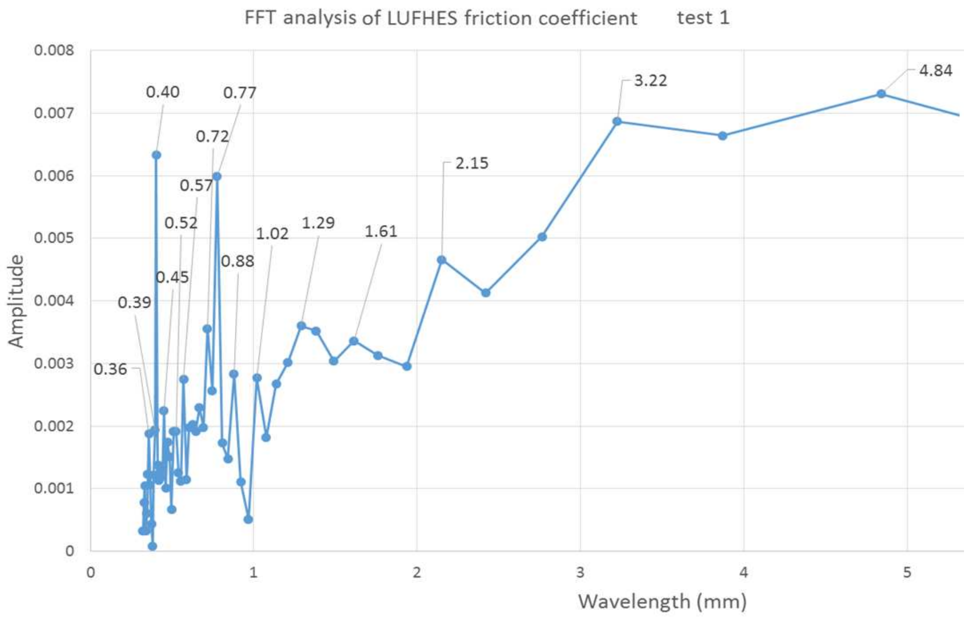


Figure 5 LUFHES friction test: (a) dynamic coefficient of friction curves; (b) FFT analysis

Table 1 Comparison of wavelengths in LUFHES and KES-F roughness test

Wavelength groups (mm)	Wavelength obtained in FFT analysis of LUFHES friction test (mm)		Wavelength obtained in FFT analysis of KES-F Roughness test (mm)	
	Test 1	Test 2	Round 1	Round 2
0.3-0.4	0.36, 0.39	0.35, 0.39	0.38	0.39
0.4-0.5	0.40, 0.45,	0.40, 0.47	0.42, 0.45, 0.48	0.42, 0.46
0.5-0.6	0.52, 0.57	0.59	0.52, 0.55	0.53, 0.57
0.6-0.7	/	0.65	0.64	0.63, 0.69
0.7-0.8	0.72, 0.77	0.70, 0.76	0.7, 0.75	0.79
0.8-0.9	0.88	0.82	0.86	0.89
0.9-1.0	0.91	/	0.91	/
1.0-2.0	1.02, 1.29, 1.61	1.00, 1.18, 1.46, 1.72	1.04, 1.31, 1.67	1.01, 1.21, 1.31, 1.59
>2.0	2.15, 3.22, 4.84	2.37	2.01, 2.31, 3.01, 6.02	2.01, 2.74, 3.77

CONCLUSIONS

It is shown from the comparison of FFT analysis of LUFHES fabric-to-fabric self-friction test and KES-F roughness test that both LUFHES and KES-F test cannot obtain wavelengths less than 300um, therefore the fine texture structure of the fabric surface could not be obtained. However, almost all of the wavelengths obtained from KES roughness test could be found corresponding ones in LUFHES results. With the consideration of the fact that wavelength from KES-F roughness tester is obtained from fabric texture profile and the wavelength from LUFHES is from the variance of the amplitude of the vibration induced from fabric friction process, the highly agreement of the FFT spectra analysis is an indication that LUFHES fabric-to-fabric self-friction test is a promising testing method for objectively assess the perception of fabric roughness and smoothness.

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