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Model for contact between finger and sinusoidal plane to evaluate adhesion and deformation component of friction ☆

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ABSTRACT

One of the main parameters affecting finger friction, friction-induced vibrations in the finger, and consequently tactility is surface topography. Recently Skedung et al. performed finger friction measurements on fine controlled surfaces. These surfaces were sinusoidal with wavelengths from 0.27 to 8.8 μm and amplitudes from 0.007 to 6 μm. Building on those tests an analytical model for the contact was developed to explain the differences in friction coefficient. The contact was modelled as trapezoids in a circular pattern pressed against a sinusoidal plane. Results showed that the calculated contact area and therefore friction coefficient corresponded well with the measurements. This model can be used to see how the different surface parameters influence friction.

1. Introduction

One of the main parameters affecting finger friction, friction-induced vibrations in the finger, and consequently tactility is surface topography. Different peaks, amplitudes and spatial distributions affect, for example, the contact area and adhesion forces, deformation and generated vibrations in the finger. All of these factors have a direct influence on how a surface feels but they also influence each other. A smooth surface has a larger contact area that directly gives higher adhesion force. However, a rough surface affects the deformation and vibrations induced in the skin. So determining friction or feel of a surface involves many parameters that depend on each other. Many product surfaces have either a shiny, matte or textured surface, and knowing how different surface parameters affect the contact area, friction and therefore feel could help one choose a desired surface [1–4]. Recently, Skedung et al. performed finger friction tests on 17 fine controlled surfaces [5]. These surfaces were made of polymer and had a sinusoidal topography with wavelengths of 0.27–98.8 μm and amplitude of 0.007–6 μm. The friction tests were conducted with controlled force, speed, temperature and humidity and gave average friction coefficients from 0.3 to 1.2 for the different surfaces. All tests were performed with an average normal force of 1 N and the finger was slid perpendicular to the sinusoidal ridges. Since the test surfaces were made of the same material the explanation for the different results could be linked to the surface topography. The aim of this work was to make a model that gives the real contact area, interfacial shear strength and deformation depth of the skin. And further from these calculate the adhesion and deformation component of friction. Comparing these with the measured friction coefficient indicates from where the differences in friction coefficient originate.

2. Model

The fingerprint was assumed as a circular pattern of flat, trapezoidal ridges (Fig. 1). Several skin measurements have shown that the finger ridges, especially in contact with a flat surface, are principally trapezoids [6,7], however, the ridge patterns come in different formations, for example arch, loop or whorl [8]. For this model concentric circles was used, which is quite similar to the whorl and also matches well with other formations.

Bringing this fingerprint model in contact with the sinusoidal test surface results in line contacts all over the surface (Fig. 1). The total contact length was calculated analytically and depends on the radii of the circles and the wavelength of the test surface. The contact width and deformation depth for the contact between flat skin on the ridges and the sinusoidal surface was calculated from a model on rough contact by Westergaard [9]. The contact width multiplied with the contact length gave the real contact area from which the adhesion friction coefficient could be calculated. For the deformation component of friction two different models were

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used and compared. First one was a plastic model of a ploughing cylinder [10] and the second one was a viscoelastic model of a cylinder sliding on flat surface [11].

2.1. Micro contact model

With the heads of the finger ridges being considered flat and relatively large compared to the scale of the test surfaces the local contact between waves of the test surface against the top of the ridge was modelled as a flat on a sinusoidal plane. The soft plane (here finger) is deformed by the stiff sinusoidal surface (Fig. 2), giving a deformation depth δ and contact width $2a$ from a model by Westergaard [9] based on Hertzian contact theory. The contact width $2a$ is given by:

$$2a = 2\lambda/\pi \sin^{-1}(\bar{p}/p^*)^{1/2} \tag{1}$$

where λ is the wavelength, $\bar{p}$ mean surface pressure given from dividing normal force with apparent contact area, and p^* the pressure needed for full continuous contact which is given by:

$$p^* = \pi E^* \Delta/\lambda. \tag{2}$$

The combined Young's modulus E^* is calculated from the Young's modulus's and Poisson's ratios for the two surfaces, and apparent contact area A can be measured or approximated for the contact. Data for the polymer in the test surfaces was given from the manufacturer, and for the skin they were chosen from earlier tests [12–14]. The deformation of the skin seen earlier (Fig. 2) is a sinus wave with the same wavelength as the test surface, and with amplitude of zero when the force is zero and with maximum amplitude that equals the amplitude of the test surface. The deformation depth δ is also calculated from the model by Westergaard [9] and given by:

$$\delta = \left(1 - \nu_f^2\right)\lambda/\pi E_f \, \bar{p} \cos(2\pi x/\lambda) \tag{3}$$

where ν_f is the Poisson's ratio for the skin, E_f is the Young's modulus for the skin (index f for finger) and $\bar{p}$ is the same mean surface pressure as used in Eq. 1 above. The variables used to calculate the contact width and deformation depth are shown in Table 1.

The calculations were made for each test surface. Table 2 below shows the wavelengths λ and amplitudes Δ for all the test surfaces.

2.2. Macro contact model

Dimensions for the ridges and therefore the circles for the fingerprint were taken from a microstructural cross-section of a middle finger using optical coherence tomography [6]. The distances obviously vary but a ridge top width and distance of 250 μm (Fig. 3) was considered average. This also gives a contact ratio against a flat plane of 50%, which corresponds well with the literature [8,15]. This pattern was extended out to a 6 mm radius to resemble the finger used in the friction tests.

Table 1
Used properties for the skin, test surface, apparent contact area and normal force used when calculating the contact width and deformation depth.

Young's modulus for finger (E_f). [12]	0.2 MPa
Poisson's ratio for finger (ν_f). [13]	0.4
Young's modulus for test surface (E_s).	1.38 MPa
Poisson's ratio for test surface, (ν_s).	0.4
Combined Young's modulus (E^*).	0.21 MPa
Surface area	113 mm^2
Normal force	1 N

Table 2
Wavelength and amplitude for the test surfaces used in Skedung et al.'s friction measurements [5].

Surface	Wavelength λ [μm]	Amplitude Δ [μm]
1	0.27	0.007
2	0.76	0.013
3	0.87	0.022
4	17.5	1.2
5	17.6	1.2
6	20.5	1.6
7	25.0	3.1
8	25.1	2.1
9	31.2	2.4
10	34.0	4.0
11	37.4	4.5
12	39.9	3.3
13	42.9	3.6
14	46.5	4.0
15	70.7	1.9
16	90.0	3.4
17	98.8	6.0

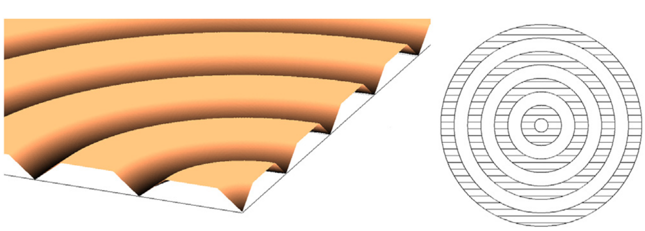

Fig. 1. Section of assumed fingerprint used in this model to the left and contact zones on finger print to the right.

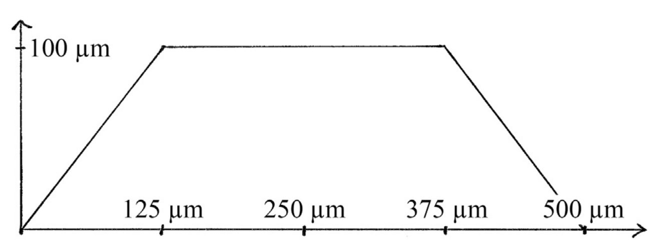

Fig. 3. Dimensions for the trapezoidal ridges that the model was based on.

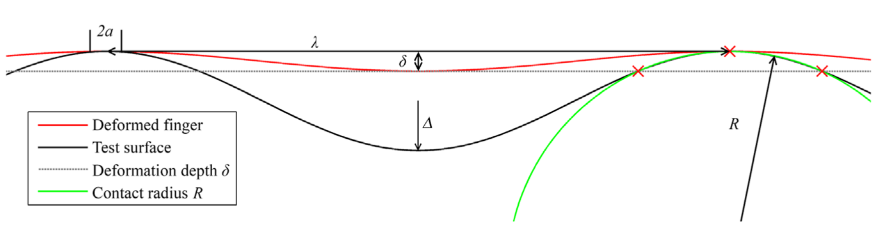

Fig. 2. Model of contact between flat skin and the test surface. Given parameters are the amplitude of the test surface Δ and wavelength λ. Deformation depth δ, contact width $2a$ and estimated contact radius R were calculated. Red crosses show the points from which contact radius were calculated.