Tribology International 101 (2016) 49–58

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

A contact mechanics interpretation of the duplex theory of tactile texture perception

Ramona Fagiani [a,*], Marco Barbieri [b]

[a] Department of Industrial Engineering, University of Parma, Parco Area delle Scienze, 181/A, 43100 Parma, Italy
[b] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli 10/1, 41125 Modena, Italy

ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form
24 March 2016
Accepted 28 March 2016
Available online 4 April 2016

Keywords:
Induced vibration
Duplex tactile perception
Skin tribology
Mechanoreceptors
Surface texture

ABSTRACT

The tactile perception of a surface texture originates from scanning a finger on the surface. This kind of sliding contact activates the mechanoreceptors located into the skin, allowing the brain to identify the object and to perceive information about the scanned surface. Perception is collected by mechanoreceptors either by sensing pressure or by sensing vibration: the first mechanism is typical of large spaced surface textures, while the second is necessary to perceive finer textures. These different behaviors are well known in the literature as the duplex perception mechanism. In the present paper a numerical model describing finger-surface scanning is introduced in order to investigate the relationship between contact induced vibrations and scanning conditions. The model has been validated by experimental comparisons in a previous work. The perception model is used to develop a parametric analysis of the vibration induced from the finger-surface scanning as a function of surface geometry, scanning speed and contact force. The proposed parametric analysis points out the minimum number of parameters needed to describe the tactile perception of a periodic texture, and it shows the tribological reasons for which duplex perception mechanism is an effective biological evolution towards optimal tactile perception.

1. Introduction

Object recognition is due to an appropriate combination of the different senses that supplies the global information. For example, sight furnishes information on object localization and shape, while touch provides information about physical properties like texture and compliance. Tactile perception is allowed by the activity of the cutaneous sensory neurons located in the skin, joints and muscles. They can be divided into three classes according to sensing modality [1–6]: nociceptive units, thermoreceptive units and mechanoreceptive units. The nociceptive units are activated both by mechanical and thermal stimuli which exceed a threshold corresponding to a damaging level and to pain sensation, while the other afferents got their name from the stimulus they are most sensitive to. It should be noted that tactile perception and judgment are not just a physical mechanism but also involve physiological background based on memories and social factors. Thus it is difficult to well evaluate and predict the perception process. On the other hand, in the last years, haptics has received tremendous attention for its implications in a large range of everyday applications such as: ergonomics, tele-diagnosis, remote surgery and manipulation, virtual and augmented reality, identification of surface imperfections, intelligent prostheses and robotic assistants. Haptics is also relevant for specialized fields: textile products design and cosmetic products evaluation. The commercial competitiveness of these products is strongly related to their tactile feeling and to acceptance of them by hand [7–17].

The aim of the project is to approach the haptic sense by directly investigating the vibrations induced by finger/surface scanning, which are the direct cause of the tactile perception coded by the brain. When the hand moves to scan a surface, the interaction between the finger skin and the surface roughness produces a vibration that propagates into the skin causing a space time variation of the skin stress state that induces the response of the mechanoreceptors, allowing the brain to perceive information about object surfaces [18–22]. In such a way, by focusing the attention on the consequence of the sliding contact, *i.e.* on the induced vibrations, the analysis takes into account the complexity of the tactile perception mechanism, directly considering the combination of contact parameters. In this context, the goal is to analyze the induced vibrations highlighting their dependence on contact and scanning conditions. In the present work vertical oscillations are considered: this is not in contrast with other works

---

[*] Corresponding author.
E-mail addresses: ramona.fagiani@gmail.com (R. Fagiani), mark@unimore.it (M. Barbieri).

http://dx.doi.org/10.1016/j.triboint.2016.03.031
0301-679X/

found in the literature, where tangential vibrations are investigated, since the presence of dynamic friction can originate tangential oscillations having the same pattern of those observed in the vertical direction. Zahouani et al. [23] developed a model of finger–texture interaction considering a fingerprint and a rough spherical indenter; Amaied et al. [24] proposed finite element modeling and experimental measurements of tangential vibrations in a finger–texture contact; Derler et al. [25] pointed out the occurrence of stick–slip phenomena in finger-surface contacts in pulling motion.

In the present paper, the development of a numerical model of the induced vibrations in finger/surface scanning is described. The model takes into account finger and surface geometries, material properties, normal contact force and scanning velocity. The model is used to develop a parametrical analysis of vibration as a function of surface geometry, scanning speed and contact force. The model has been previously validated by a comparison between the vibration spectra obtained by the numerical model and the ones obtained experimentally [26].

2. Numerical model

In the present paper, the model proposed in Ref. [26] is considered: the equations are put in non-dimensional formulation, and solved for different values of the dimensionless parameters. Vibration between a finger and a periodical rough surface sample is described as follows:

$$\frac{k}{L}\int_0^L \overline{\delta}(x,z,t)\,dx = w \tag{1}$$

where k is the equivalent contact stiffness, L is the contact length along the fingertip, w is the external load. Fig. 1 proposes a graphical representation of Eq. (1).

$\overline{\delta}$ is the punctual approach of the mating surfaces, in the no adhesion hypothesis; δ is the corresponding geometrical approach defined as in the following:

$$\overline{\delta}(x,z,t) = \begin{cases} \delta(x,z,t) & \text{if } \delta(x,z,t) \geq 0 \\ 0 & \text{otherwise} \end{cases}$$
$$\delta(x,z,t) = a_2 \cos\left(\frac{2\pi(x-ut)}{\lambda_2}+\phi\right) - a_1 \cos\left(\frac{2\pi x}{\lambda_1}\right) - z \tag{2}$$

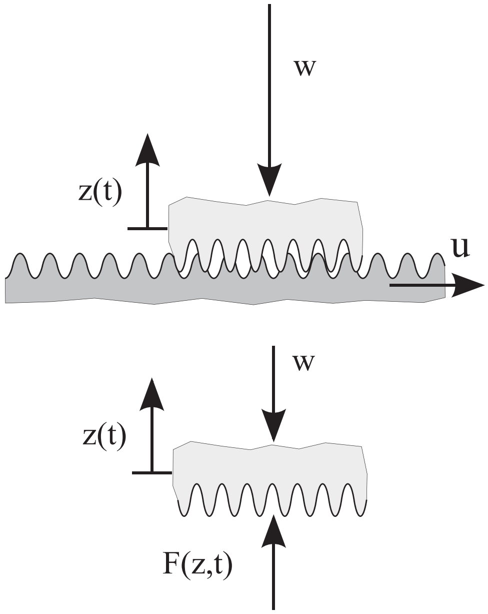

Fig. 1. Quasi-static model of the contact with asperities, Ref. [26].

where a_1 and a_2 are the equivalent roughness of the finger and of the sample surface; λ_1, λ_2 are the spatial periods of the two surfaces; u is the relative sliding speed of the surface with respect to the finger; ϕ is a phase shift between the two sine profiles. In the present paper $\phi = \sqrt{2}$ is chosen in order to avoid introducing spurious periodicities. The equivalent roughnesses a_1 and a_2 can be defined in terms of the mean arithmetic roughness R_a of the surfaces as in the following:

$$R_a = \frac{1}{\lambda_1}\int_0^{\lambda_1}\left|a_1 \cos\left(\frac{2\pi x}{\lambda_1}\right)\right| dx = \frac{2}{\pi}a_1 \Rightarrow a_1 = \frac{\pi}{2}R_a \tag{3}$$

The equivalent contact stiffness k in the Winkler approach is defined assuming Hertzian contact between the ridges of the finger and those of the sample surface; this choice is discussed in Ref. [26]. According to the Hertzian assumption, and using the formulation proposed in Ref. [27], the stiffness is computed as follows:

$$k = \frac{k_{el}}{\ell}L^2; \quad \frac{k_{el}}{\ell} = 1.18\frac{E^*}{a}$$
$$E^* = \left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^{-1} \tag{4}$$

where ℓ is the equivalent depth of the elastic foundation, and a is the half-width of the line contact between the ridges. Since the global load w is shared by a number of ridges given by L/λ_{eq}, and the length of each ridge is L, a is computed as in the following:

$$a = \sqrt{\frac{4w_{\ddagger}R_{eq}}{\pi E^*}}; \quad w_{\ddagger} = \left(\frac{w}{L}\right)\left(\frac{\lambda_{eq}}{L}\right) = \frac{w\lambda_{eq}}{L^2}$$
$$\lambda_{eq} = 2\frac{\lambda_1\lambda_2}{\lambda_1+\lambda_2}; \quad R_{eq} = \left(\frac{1}{R_1}+\frac{1}{R_2}\right)^{-1} = \left(\frac{4\pi^2 a_1}{\lambda_1^2}+\frac{4\pi^2 a_2}{\lambda_2^2}\right)^{-1} \tag{5}$$

A significant issue of the proposed model is setting the elastic moduli of the skin. Indeed, many authors have pointed out that Young's modulus is highly variable for different skin layers: in particular, the outer layer (*stratum corneum*) is significantly stiffer than the whole skin [28–33]. In order to overcome this issue, it is useful to look for experimental results on tactile perception. The experiments show that a subject can usefully perceive the surface roughness for a contact load ranging between 0.05 and 1.8 N [26,34]. A contact analysis based upon Hertzian assumptions shows that for a load of 1 N over a fingertip having a surface of 1 cm^2, the stress is negligible out of the *stratum corneum* [26]. A recent work of Liang et al. [35] was successful in measuring the Young's modulus of the outer skin layer *in vivo* by means of dynamic optical coherence elastography; their conclusion was that the Young's modulus of dry skin at a driving frequency of 50 Hz is 101.2 kPa, and that at such low frequency mechanical properties are primarily due to the *stratum corneum*. According to Liang's results, a Young's modulus of 101.2 kPa and a Poisson's ratio of 0.5 can be assumed in Eq. (4). Note that the computations performed in [26] were performed with $E = 60$ kPa and a wrong value of 6 MPa was erroneously reported.

2.1. Dimensionless equations

In order to put Eq. (1) in non-dimensional form, the following substitutions are performed:

$$\Delta = \frac{\delta}{a_1}; \quad Z = \frac{z}{a_1}; \quad X = \frac{x}{\lambda_1}T = \frac{t}{t^*}; \quad t^* = \frac{\lambda_1}{u}\mathrm{W} = \frac{\mathrm{w}}{\mathrm{w}^*}; \quad \mathrm{w}^* = \frac{\mathrm{k}\mathrm{a}_1\lambda_1}{L} \tag{6}$$

therefore, thanks to the proper choice of w*, the dimensionless equation is:

$$\int_0^{\tau} \overline{\Delta}(X,Z,T)\,dX = \mathrm{W} \tag{7}$$

where τ is the number of ridges in a fingerprint. Along with τ, it is