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Ergonomic Vibrotactile Feedback Design for HMI Applications

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Abstract: Wide range of Human Machine Interfaces (HMI) contains vibratory actuators to provide the user with vibrotactile feedback. From the engineering aspect of practical applications, it is necessary to investigate the human sensory system. Goal of the research is to obtain vibrotactile stimulation strategies which are matching to the characteristics of the human mechanoreceptors and are feasible considering the dynamics of the actuator-human mechanical system. The paper surveys the vibrotactile sensitivity of the human cutaneous mechanoreceptors and proposes a system theoretical representation in term of transfer function.

Key words: Cognitive infocommunication, HMI, Biologically inspired engineering.

1 Introduction

The market of devices (mobile phones, PDAs, game controllers etc.) providing some kind of vibrotactile feedback is continuously growing. The maximization of the transmittable information via vibrotactile channel is an obvious ambition. Importance of vibrotactile feedback strategies is also significant in the so called sensory substitution based rehabilitation and human-machine interaction [8,9]. From the engineering aspect of practical applications, it is necessary to investigate the human vibrotactile sensory system and the feasible stimulation using vibrotactile actuators.

Goal of the investigation is to obtain vibrotactile stimulation strategies which are optimally stimulate the human sensory system, and are feasible considering the dynamics of the complex actuator-human tissue mechanical system. In this paper, authors give a comprehensive summary of the vibrotactile sensitivity of the human cutaneous mechanoreceptors and propose a system theoretically correct representation in terms of transfer function for the stimulation of the fingertips.

Authors aspire to provide the synthesis of the knowledge on the vibrotactile sensation of human hand using the formalism of system and information theory. The exposed results are useful for engineers and researchers to design ergonomic vibrotactile devices, filling the gap between the neuro-science and the engineering application. To do so, the properties of the human vibrotactile sensation and the vibration actuators must be known quantitatively to reach the best matching. The paper contains the very first result of this effort.

The above described research topic belongs to the discipline of cognitive infocommuncation. Relying on cognitive processes and their mathematcal models, cognitive infocommunication provides effective communication between the human brain and computerized systems like robots or control system interface modules.

The paper is sectioned as follows: Section 2 surveys the mechanoreceptors the human skin. Section 3 describes the method and the result of filter fitting onto measured vibrotactile threshold data. Section 4 summarizes the paper.

2 Vibrotactile sensitivity of the human skin

The analysis of the human skin's mechanoreceptors and those frequency domain characteristics is indispensable in this research. This knowledge grounds for the selection of proper vibrotactile actuators and the design of efficient stimulation strategies.

Basically, there are four types of receptors in the skin responsible for transducing information on mechanical interaction:

Merkel endings: They have high spatial resolution, located mostly in areas where sensory perception is acute, such as the fingertips. They have a sustained response to mechanical deflection (pressure) of the tissue. They are the most sensitive of the four main types of mechanoreceptors to vibrations at low frequencies up to 10-15 Hz. Because of the sustained response, Merkel nerve endings are known as slowly adapting types (SA1).

Pacinian corpuscles: They detect gross pressure changes and vibrations and are rapidly adapting (phasic) receptors. Considerably larger but fewer in number than Merkel cells.

These corpuscles are especially susceptible to vibrations, which they can sense even centimeters away. Their optimal sensitivity is 250 Hz and this is the frequency range generated upon finger tips by textures made of features smaller than 200 µm.

Ruffini endings or Ruffini corpuscles are slowly adapting mechanoreceptors, located in the deep layers of the skin. They are sensitive to skin stretch, as well as angle change within joints with a specificity of up to 2 degrees, and contribute to the kinesthetic sense. It is believed to be useful for monitoring slippage of objects along the surface of the skin, allowing modulation of grip on an object.

In the design of commercial vibration motors the frequency of the highest gains is determined using the human hand frequency sensibility diagram made by Verillo et al. From Verillo's results we can read that the human hand is the most sensible for the vibrations in the range of 200-300Hz, which is similar to the frequency sensibility of the Pacini corpuscules. The quick adaptation property of the Pacini corpuscules is a disadvantage in the vibro-tactile applications, because after the fast adaptation the user feel reduced vibration stimulus which may runs to operator fault due to the false perception.

Meissner afferents innervates the skin more densely (about 150/cm^2 at the fingertip) than the Merkel endings (SA1) do. They are insensitive to the static skin deformation, but four times more sensitive to the dynamic deformation than the Merkel afferents. Meissner afferents are rapidly adapting types (RA). The receptive field of it is about 3-5 mm in diameter and it responds uniformly in this area, therefore the spatial resolution is less good.

Besides the Pacini corpuscules, Merkel endings are also relevant. The two types of receptors are complementing each other in the sensation of long-term complex mechanical effects. Authors assume that in the shaping of tactile feedback those stimulation strategies are beneficial, where both of the receptor types are stimulated at the optimal frequency range respectively in such a way that none of them could adopt to the present stimulus.

Table 1 shows a perspicuous summary of the above described properties of the human mechanoreceptors. References to the corresponding literature are also written in the table.

3 Vibrotactile sensitivity as TF

Soneda and Nakano published experimental results on vobrotactile sensation of human fingertips [10]. They have collected the results of former studies as well. We have used the measured vibrotactile threshold data as reference for the filter fitting. Vibrotactile sensitivity is defined as the reciprocal of the vibrotactile threshold. The MATLAB basic fitting utility was used for rational fraction polynomial fitting. Fig 1. shows the measured data from [10] and the fitted curve. The fitted rational fraction polynomial has been transformed into transfer function. Unfortunatelly, the roots of the fraction polinomial are complex. The resulted transfer function $F_{vs}(s)$ depicted by the equation 1. Fig 1. shows, that the fitted curve describes the vibrotactile sensitivity well, especially in the frequency range of 10-1000 Hz.

Please note, that the investigated case covers only a small and special issue of the vibrotactile sensation. The vibrotactile sensation threshold and so the sensitivity ifluenced be many parameters namely the contact load, contact area, location of the stimulus, stimulus frequency and the contact temperature. In the future, we plan to model the effect of a part of these parameters. Another important factor is the adaptation property of the mechanoreceptors. Describing the sensitivity as a time invariant transfer function does not handle the adaptaion. It is also a subject of further investigation.

Table 1. Properties of the human mechanoreceptors

	Pacinian Corpuscles (RA2)	**Ruffini corpuscles (SA2)**	**Meissner Corpuscles (RA1)**	**Merkel receptor (SA1)**
Skin type [1,2]	Glabrous & Hairy	Glabrous & Hairy	Glabrous	Glabrous
Location [4]	Dermis and deeper tissues	Connective tissue of the dermis	Dermis, in dermal ridges	Basal layer of the epidermis
Density [4,5]	~75/cm2 at the fingertip	~75/cm2 at the fingertip	~150/cm2 at the fingertip	~100/cm2 at the fingertip
Sensitivity [1,2,5,7]	Vibration (normal and parallel) Distant events through tranmitted vibrations High-frequency stresses	Skin stretch Lateral force Skin stretch direction Horizontal tensile strain	Edges & Corners Curatures Slip between skin and an object	Points Edges & Corners Curvatures Strain energy density
Response properties [5,6]	Extreme sensitivity (10 nm or less at 200 Hz, normal direction) Intense rejection of low-frequency stimuli, Phase locked response to stimuli less than 100-150 Hz	not well understood	Greater sensitivity but poorer spatial resolution and limited dynamic range relative to SA1 afferents	Linear response to skin deformation (min 1500 um depth) (4-5 degree orientation at the fingertip)
Stimulation Type [1,2,5]	High frequency skin motion, Vibrations	Skin motion, sustained skin deformation	4x more sensitive to dynamic deformation than SA1	10x more sensitive to dynamic than to static stimuli
Responsibility [5]	High fidelity neural image of transient and vibratory stimuli	perception of stretching sensing finger position	Robust neural image of skin motion, Detection slip between skin and an object, Grip control	Form & Texture perception, Neural image of the stimulus and its orientation, Independent of contact force
Spatial resolution [1,2,5]	Very poor (2 - 10 cm)	Poor (1 cm)	Fair (3 - 5 mm)	Good (0.5 mm) (Smaller than RF size!)
Receptive field size [4]	Large	Large	Small (3-5 mm)	Small (2-3 mm)
Adaptation [3,4]	Fast	Slow	Fast	Slow
Static response [4]	No	Yes	No	Yes
Percent on palm [4]	13%	19%	43%	25%
Stimulation Freq. Range (Hz) [1,2,3]	100-1000	0.4-100	2-40	0,4-10
Interstimulus Interval [1,2]	5 ms to percieve separate stimuli, 20 ms to percieve stimuli order			

$$F_{vs}(s) = \frac{1.848s^3 + (-2648i)s^2 - 2.83e6s + 5.611e7i}{s^3 + (-2302i)s^2 - 7.765e5s + (-1.29e9i)} \quad (1)$$

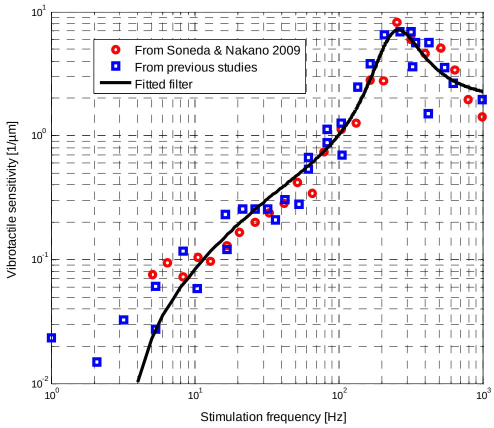

Fig. 1. Vibrotactile sensitivity of human fingertip and the fitted transfer function

4 Summary

In this paper we attempted to introduce an approach for vibrotactile feedbeck design. Authors reviewed the human vibrotactile sensory capabilities from the aspect of vibrotactile feedback. A filter characteristic was fitted onto the measured data of the vibrotactile sensitivity of the human fingertips using well published (in Neurophysiology) experimental data as reference. The proposed filter could be applied in design and testing of vibrotactile stimulation strategies.

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