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TNO report

DV3 2005-A75

Tactile Displays and Elastic Waves

20061027001

Date	September 2005
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Classification report	Ongerubriceerd
Classified by	Maj T. Schattorie
Title	Ongerubriceerd
Managementuittreksel	Ongerubriceerd
Abstract	Ongerubriceerd
Report text	Ongerubriceerd
Appendices	Ongerubriceerd
Copy no	6
No. of copies	18
Number of pages	31 (incl. appendix, excl. RDP & distributionlist)
Number of appendices	1

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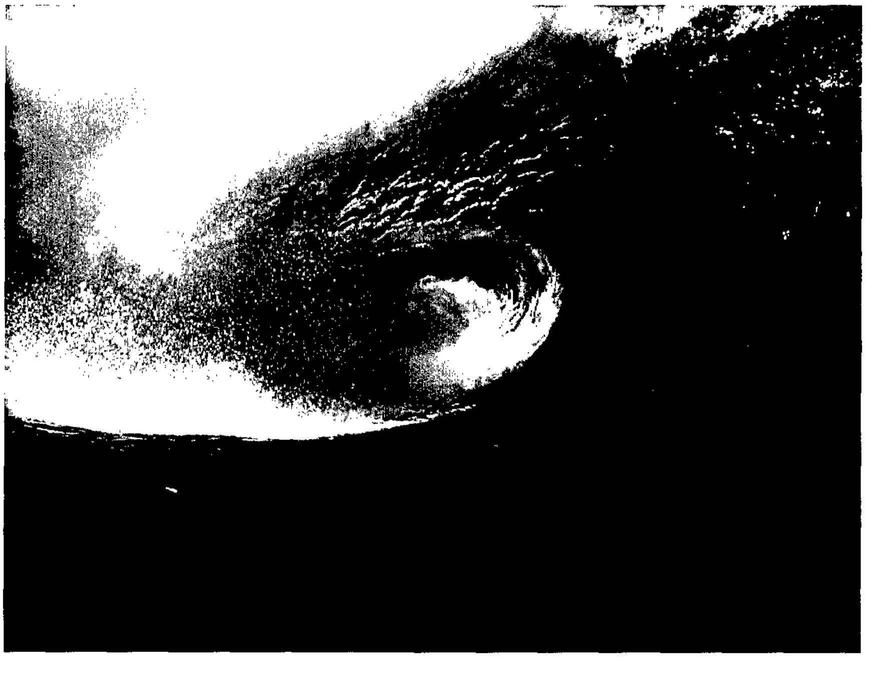
Tactiele displays en elastische golven

Tactiele displays zijn displays voor de huid, zoals beeldschermen visuele displays zijn voor de ogen. Een bekend voorbeeld is de trillende mobiele telefoon. In de mobiele telefoon zit een trilmotortje dat aangaat bij een binnenkomend gesprek. TNO Defensie en Veiligheid heeft een tactiel display in een vest met wel 64 van deze trilmotortjes, ook wel tactors genaamd.



Probleemstelling

Om op zo'n groot display informatie duidelijk af te beelden moet ervoor gezorgd worden dat de trillingen van de tactors zo lokaal mogelijk op de huid worden aangeboden. De trillingen, ook wel elastische golven genoemd, mogen zich niet te veel verspreiden door de huid of door het materiaal waarin de tactors zitten bevestigd. In het huidige tactiele vest gebeurt dit wel. In opdracht van het Ministerie van Defensie is een Nationaal Technologie Programma gestart, waarin demonstrators zullen worden gemaakt voor een nieuwe generatie tactiele displays. Een onderdeel hiervan is het opstellen van ontwerpcriteria voor tactiele displays, die de verpreiding van trillingen minimaliseren.

Beschrijving van de werkzaamheden

De ontwerpcriteria zijn opgesteld met behulp van een literatuurstudie waarin de generieke theorie van elastische golfgeleiding in materialen is gecombineerd met kennis over de structuur van de huid.

Toepasbaarheid

De ontwerpcriteria die uit deze literatuurstudie volgen, zullen worden meegenomen in het ontwerp van een nieuwe generatie tactiele displays en ervoor zorgen dat informatie beter kan worden overgebracht op de huid.

Contact en rapportinformatie

PROGRAMMA

Programmabegeleider
-

Programmaleider
-

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-

Programmanummer
-

Programmaplanning
Start -
Gereed -

Frequentie van overleg
Met de projectbegeleider werd incidenteel gesproken over de invulling en de voortgang van het onderzoek.

PROJECT

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Projecttitel
TACT

Projectnummer
013.44436

Projectplanning
Start mei 2004
Gereed oktober 2005

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TNO-rapportnummer
TNO-DV3 2005 A075

Opdrachtnummer
-

Datum
september 2005

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Rubricering rapport
Ongerubriceerd

Samenvatting

Probleemstelling
Wanneer tactoren van een tactiel display in een drager, zoals een vest of een stoel, zijn gemonteerd spreiden die vibraties zich uit door de huid en de omgeving wat tot gevolg heeft dat de trillingen niet meer lokaal worden waargenomen en moeilijker zijn te onderscheiden. Vibraties in een dergelijk systeem moeten lokaal zijn voor een goede detectie; spreiding door de huid of de omgeving moet geminimaliseerd worden.

Werkwijze
Er is een literatuurstudie gedaan die een kwalitatieve beschrijving van de tactor-skin interface geeft. Generieke golfgeleidingstheorie en kennis van de structuur van de huid zijn gecombineerd om ontwerpcriteria voor tactiele displays te bedenken die de verspreiding van trillingen minimaliseren.

Resultaten
Volgens de literatuur kunnen drie soorten golven zich voortplanten in de huid en de drager waarin de tactoren zitten: schuifgolven, drukgolven en oppervlaktegolven. Zij planten zich radieel voort met verschillende snelheden en met verschillende golflengtes. De golven spreiden zich en doven uit, maar ze kunnen ook energie verliezen door frictie. Elke type golf dooft met een andere snelheid uit.

Conclusies en aanbevelingen
Tactoren die een minimale spreiding van trillingen door de huid of de omgeving hebben trillen parallel aan het huidoppervlak met een frequentie van 200 Hz. De tactoren zouden aan de huid gelijmd moeten zijn of gecoat met een materiaal, zodat de tactor niet over de huid kan glijden. Het zou nog beter zijn als er een materiaal met een dikte van een kwart golflengte tussen de tactor en de huid wordt geplaatst. Dit zorgt voor een goede overdracht van vibratie-energie. Wanneer de tactoren niet slipvrij op de huid bevestigd kunnen worden, dan is het beter verticaal op de huid te trillen. De grootte van het contactoppervlak van de tactor met de huid moet klein zijn. Tussen de tactor en de drager zou een zacht materiaal met daaromheen een stijf materiaal geplaatst moeten worden, zodat er zo weinig mogelijk trillingsenergie wordt overgebracht op de drager en zoveel mogelijk energie naar de huid wordt gereflecteerd. Als laatste zou de grootte van trillende oppervlakten van bijvoorbeeld de behuizing van de tactor minimaal moeten zijn, om ervoor te zorgen dat de tactoren geen lawaai maken.

Summary

Purpose
When tactors of a tactile display are mounted in a tactor carrier, for example a vest or a chair, vibrations will spread out through the skin and the tactor carrier. As a result the localisation of the vibration sources is reduced. Vibrations in such a system should be local to ensure good detection; spreading through the skin or the environment has to be minimised.

Method
A literature review that gives a qualitative description of the tactor-skin interface has been carried out. General wave propagation theory and knowledge about the structure of the skin haven been combined in order to create several design criteria that minimise the spreading of vibrations.

Results
From the literature it became clear that three types of waves can propagate through the skin and the tactor carrier: shear waves, compression waves and surface waves. They propagate through material in a spherical fashion at different propagation velocities and with different wavelengths. The waves spread out and dampen, but they can also loose energy by friction. Each type of wave dampens at a different rate.

Conclusions and Recommendations
Tactors that have a minimal spreading of vibrations through the skin or the tactor carrier oscillate parallel to the skin and use a stimulation frequency of 200 Hz. The tactors should be glued to the skin or coated with a material that does not slip easily. It is even better to insert a material with a thickness of a quarter of a wavelength between the tactor and the skin. This results in a better transfer of vibration energy. When the tactors cannot be attached free of slip to the skin, it is better to use tactors that oscillate perpendicular to the skin. The size of the contact area between the tactor and the skin should be small. Soft material encased in stiff material should be used between the tactor carrier and the tactor in order to reduce the amount of vibration energy emitted to the tactor carrier and to reflect energy to the skin. Finally, the area of vibrating surfaces of e.g. the housing of the tactor should be kept minimal to reduce the noise production of vibrating tactors.

Contents

1 Introduction

The past six year TNO has investigated how information can be displayed on the skin. It turned out that an array of vibrating elements, so-called tactors, placed close to the skin can be used as a tactile display. TNO has built several versions of a vest with 64 tactors and a belt with eight tactors. They were used in several experiments that showed that it was possible to provide the wearer of a tactile display with enough information to enable him or her to successfully hover with a helicopter, to navigate along way-points and to recover from spatial disorientation [Van Erp, Veltman, Van Veen, & Oving, 2002; Van Erp & Van Veen, 2003; Van Erp, Jansen, Dobbins, & Van Veen, 2004; Van Veen & Van Erp, 2003; Van Veen, Spapé, & Van Erp, 2004].
The current hardware of the tactile display is designed to work in laboratorial circumstances and it is not very suitable for field experiments. In the project called Tactile Displays (TACT) new, state-of-the-art hardware that can be integrated in garment is developed. It is designed to be used in the field and still provide a clear tactile sensation. Several demonstrators are designed that can show the capabilities of tactile displays on land, in the air and in the water.
In order to provide clear, local vibratory stimulation to the skin, the spreading of vibrations through the skin or the garment has to be minimised. This report is a literature review that gives a qualitative description of the tactor-skin interface when the tactors are mounted in for example a tactile vest. It combines knowledge of wave propagation in materials given in Chapter 2 with knowledge of the structure of the skin and of its mechanicals properties given in Chapter 3. In Chapter 4 design criteria for a general tactile display are composed.

2 Theory of Wave Propagation in Materials

2.1 Mechanical Properties of Materials

The propagation of waves in a material is strongly related to the mechanical properties of that material. Two important properties are the elasticity and the density (ρ) of the material. When a uniform uniaxial stress (force per surface area)

$$\sigma_x = \frac{F_x}{A} \quad [\mathrm{N/m^2}] \tag{1}$$

is applied to a rod, a change Δl in the length l of the material will occur. The relation, according to Hooke's law, is

$$\varepsilon_x = \frac{\Delta l}{l} = \frac{\sigma_x}{E} \quad \Leftrightarrow E = \frac{\sigma_x}{\varepsilon_x} \quad [\mathrm{N/m^2}], \tag{2}$$

in which E is called the Young's modulus and ε the strain. It is obvious that when the Young's modulus is high, the material hardly changes in length when stress is applied. The material thus has a high stiffness. Most materials and certainly the skin show a nonlinear relationship between the stress and the strain. The parameters are often linearised for small changes in σ or ε. Not only does a change in stress cause a change in the length of the material, but also a change in the width of the material (both in y and z direction); in the case of an elongation of the material, the width will decrease. The ratio between the relative change in width and length is called the Poisson ratio and is defined in an isotropic medium as

$$v = -\frac{\Delta d/d}{\Delta l/l} = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_z}{\varepsilon_x}, \quad -1 < v < \frac{1}{2}, \tag{3}$$

in which $\Delta d/d$ is the relative change in width. In most materials, v is between zero and a half. For $v = 1/2$ the material is incompressible and for $v = 0$ the material is fully compressible. When Hooke's law is applied to a cube, the strain-stress relation in three dimensions becomes:

$$\vec{\varepsilon} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -v & -v \\ -v & 1 & -v \\ -v & -v & 1 \end{bmatrix} \cdot \vec{\sigma}. \tag{4}$$

The inverse of Equation 4 is given by

$$\vec{\sigma} = \frac{E}{(1+v)(1-2v)} \begin{bmatrix} 1-v & v & v \\ v & 1-v & v \\ v & v & 1-v \end{bmatrix} \cdot \vec{\varepsilon}$$

$$= \begin{bmatrix} \lambda+2\mu & \lambda & \lambda \\ \lambda & \lambda+2\mu & \lambda \\ \lambda & \lambda & \lambda+2\mu \end{bmatrix} \cdot \vec{\varepsilon}, \text{ with} \tag{5}$$

$$\lambda = \frac{vE}{(1+v)(1-2v)} \quad [\mathrm{N/m^2}] \text{and } \mu = \frac{E}{2(1+v)} = G \quad [\mathrm{N/m^2}],$$

in which λ and μ are called the Lamé constants. These two are often used in the literature to describe the elastic properties of a material. μ or G is also known as the rigidity of a material, the shear modulus, or the shear elasticity; when μ is large the material will hardly change in width when uniaxial stress is applied. λ is also known as volume compressibility. Basically, λ indicates how easily particles in the material can be pulled apart or pressed together, whereas μ indicates how easily these particles can slide along each other [Weisstein, 2004b; Leijendeckers, Fortuin, van Herwijnen, & Leegwater, 1998].

2.2 Longitudinal Waves and Shear Waves

The mechanical properties mentioned above are important for understanding the propagation of two main types of elastic waves that can travel through materials: longitudinal waves, also known as P-waves or pressure waves or body waves and shear waves, also known as S-waves or transverse waves. In the first case, the oscillation of particles in the material is in the direction of the wave propagation (see Figure 1). In de latter case, the oscillation is perpendicular to the direction of the wave propagation (see Figure 2).

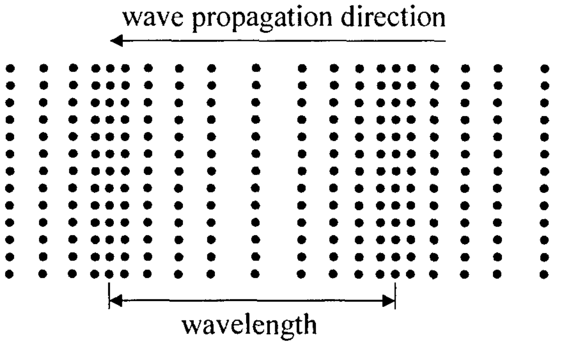

Figure 1 Schematic presentation of a plane longitudinal wave that propagates through a material. The particles in the material move back and forth.

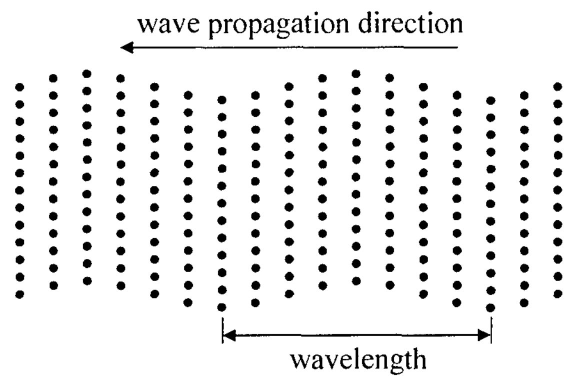

Figure 2 Schematic presentation of a plane shear wave that propagates through a material. The particles in the material move up and down.

The wave equation for plane longitudinal waves propagating in the x-direction is given by

$$\frac{\partial^2 u_x}{\partial t^2} = c_l{}^2 \frac{\partial^2 u_x}{\partial x^2}, \text{ with } c_l = \sqrt{\frac{E}{\rho} \cdot \frac{1-\nu}{(1+\nu)(1-2\nu)}} = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \tag{6}$$

in which u_x is the displacement of particles in the material in the direction of the x-axis, c_l the propagation or phase velocity, and ρ the density of the material. The propagation velocity increases monotonically for $\nu \geq 0$. The wave equation for plane shear waves is the same, except for the propagation velocity c_s:

$$\frac{\partial^2 u_y}{\partial t^2} = c_s{}^2 \frac{\partial^2 u_y}{\partial x^2}, \text{ with } c_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{\rho} \cdot \frac{1}{2(1+\nu)}}. \tag{7}$$

The displacement of the particles is now in the direction of the y-axis. The velocity of shear waves is always smaller than the velocity of body waves and decreases with ν for $\nu \geq 0$. Shear waves cannot propagate through fluids and gasses, because there is no shear coupling between particles. The general solution of the wave equation for a wave created by sinusoidal excitation and propagating in the positive x-direction is

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \Rightarrow u(t,x) = A \cdot e^{j(\omega t - kx)}, \text{ with } k = \frac{2\pi}{\lambda} = \frac{\omega}{c} \text{ and } \omega = 2\pi f. \tag{8}$$

A is the amplitude of the wave, f is the wave frequency, c is the propagation speed, k is called the wave number, and $\lambda = c/f$ is in this case the wavelength [Weisstein, 2004c; Main, 1993; Pain, 1993].
When the wave propagates through the material a dynamic force acts on each particle in that material. When on a given moment the force on a particle differs from its neighbouring particle there will be local stress. The difference in force ∂F acting on two particles close together in a material with each mass m is

$$\begin{aligned} \frac{\partial F}{\partial x} &= m\frac{\partial a}{\partial x} = m\frac{\partial^3 u}{\partial t^2 \partial x} = jmk\omega^2 A \cdot e^{j(\omega t - kx)} \\ &= mk\omega^2 A \cdot e^{j(\omega t - kx + \pi/2)} = \frac{\omega^3}{c} mA \cdot e^{j(\omega t - kx + \pi/2)}. \end{aligned} \tag{9}$$

The direction of the force is along the axis of particle motion. The maximum amplitude of the force difference increases with the wave frequency. Because of the lower propagation velocity of shear waves compared to compression waves, the force difference is larger for shear waves.

2.3 Damping of Waves

The attenuation of elastic waves is governed by two mechanisms. The first mechanism is dispersion; a wave driven by a small source will not be a plane wave, but a spherical wave. The energy of a spherical wave decreases with the square of the radius, because the area of the sphere increases with the square of the radius. As a result the amplitude decreases with the radius [Feynman, Leighton, & Sands, 1977; Petrashen, 2003]:

$$u(t,r)=\frac{1}{r}A\cdot e^{j(\omega t-kr)}. \tag{10}$$

u is a spherical wave propagating outwards and r is the radial distance from the source. The factor in front of the exponential is the amplitude in which A is constant.
The second mechanism is conversion of wave energy into heat [Yerges, 1969]. This can be caused by:

- the viscosity of the material;
- nonlinear relations (Hysteresis);
- frictional damping (Coulomb).

Mathematically, attenuation is introduced by making the Lamé constants μ and/or λ complex. The imaginary parts of μ and λ are called shear viscosity and volume viscosity respectively. As can be seen from Equation 6 and 7 complex Lamé constant results in a complex propagation speed. For the case of a shear wave the complex wave propagation velocity c_s^* becomes

$$\mu^* = \mu' + j\mu'' \Rightarrow c_s^{*2} = \frac{\mu^*}{\rho} \Rightarrow c_s^* = \sqrt{\frac{\mu^*}{\rho}} \approx \sqrt{\frac{\mu'}{\rho}}\left(1+\frac{j\mu''}{2\mu'}\right) \text{when } \mu'' << \mu'. \tag{11}$$

μ'' is often made linearly dependent of the wave frequency. Equation 11 leads to a complex wave number k^*

$$k^* = \frac{\omega}{c_s^*} \approx \sqrt{\frac{\rho}{\mu'}}\frac{\omega}{\left(1+\frac{j\mu''}{2\mu'}\right)} \approx \omega\sqrt{\frac{\rho}{\mu'}}\left(1-\frac{j\mu''}{2\mu'}\right) = k' - jk''. \tag{12}$$

When Equation 12 is combined with Equation 8, an attenuation term appears in front of the solution of the wave equation, which is dependent of the position, the wave frequency, the density of the material and the rigidity of the material:

$$\begin{aligned} u_y(y,x) &= A\cdot e^{j(\omega t-k^*x)} = A\cdot e^{-k''x}e^{j(\omega t-k'x)} \\ &= A\cdot e^{-\omega\sqrt{\frac{\rho}{\mu'}}\frac{\mu''}{2\mu'}x}\, e^{j\left(\omega t-\omega\sqrt{\frac{\rho}{\mu'}}x\right)}. \end{aligned} \tag{13}$$

In the case of a compression wave λ is often taken real and μ complex in the literature. This means that the imaginary part of k is smaller than it would be in the case of a shear wave and therefore longitudinal waves experience less attenuation than shear waves in the same material.

2.4 Reflection and Transmission of Waves

When an elastic wave hits a boundary between two different materials, part of the wave energy is reflected and part of it is transmitted very much like the reflection and transmission of light. For shear waves, the force and the tangential displacement have to be continuous across the boundary, and for longitudinal waves, the particle velocity and the acoustic pressure have to be continuous. Now let's define the wave impedance Z for the media at both sides of the boundary:

$$Z_i \equiv \rho_i \cdot c_i \ [\mathrm{kg/m^2s}], \tag{14}$$

with i being the index indicating the material. Both ρ and c are material dependent. The impedance is different for shear and longitudinal waves, because their wave propagation velocities differ. Most likely, the impedance is complex, because the propagation velocity can be complex (see Equation 11). When the material in which the incident wave travels, has index 1 and the other material index 2, then from the conditions formulated above it follows that the reflection coefficient Γ and the transmission coefficient τ are

$$\Gamma = \frac{A_r}{A_i} = \frac{Z_1 - Z_2}{Z_1 + Z_2} \text{ and } \tau = \frac{A_t}{A_i} = \frac{2Z_1}{Z_1 + Z_2} \text{ with } 1 + \Gamma = \tau, \tag{15}$$

with A_i the amplitude of the incident wave, A_r the amplitude of the reflected wave, and A_t the amplitude of the transmitted wave (see Figure 3). When the second material is very dense compared to the first material, such that $Z_2 >> Z_1$, then it follows from Equation 15 that virtually nothing is transmitted and that the wave is reflected completely. The amplitude of the reflected wave is the negation of the amplitude of the incident wave. In other words a phase shift of π rad has occurred. When $Z_1 >> Z_2$ full reflection occurs also and at the boundary the material makes large movements. Another special case is when $Z_2 = Z_1$, for instance when both materials are the same (not necessarily). As expected, the incident wave is fully transmitted and nothing is reflected [Pain, 1993].

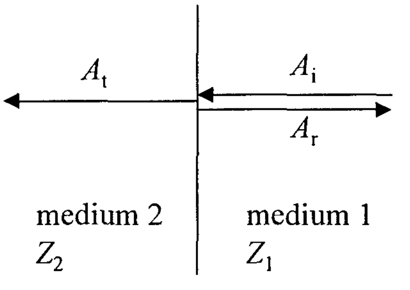

Figure 3 Reflection and transmission of a wave that hits a boundary between medium 1 and medium 2 perpendicularly. Z_i indicates the impedance of medium i. A_i is the amplitude of the incident wave, A_r of the reflected wave and A_t of the transmitted wave.

There are two interesting applications when we have two materials with different impedances. In the first application, we want to get optimal transmission of waves with as little reflection as possible. In the second application, we want to isolate the two materials from one another. In other words, transmission should be minimised. Starting with the first application, the impedances of both materials have to be matched by insertion of a third material of thickness l and impedance Z_{match} in between. Total transmission occurs when

$$Z_{match} = \sqrt{Z_1 Z_2} \text{ and } l = \frac{\lambda_{match}}{4} = \frac{2\pi c_{match}}{\omega}, \tag{16}$$

with λ_{match} the wavelength of the wave in the inserted material. One can see that the matching impedance and the thickness are different for shear and longitudinal waves. Complete transmission only occurs for one wave frequency [Pain, 1993].
Isolation requires the opposite, namely an impedance mismatch. To reduce transmission a material has to be added in between that has an impedance that differs greatly from the impedances of the materials at both sides. This causes almost total reflection. When a material with a large impedance is inserted, it needs to be a stiff, heavy material and that is not practical. A material with a small impedance needs to have a resonance frequency that is lower than the wave frequency and has a low shear modulus. Care should be taken that there are not unforeseen rigid connections between the two materials on both sides of the inserted layer [Yerges, 1969].
The concept of wave reflection and transmission can be extended from one dimension to two dimensions. Now the wave number as well as the propagation direction is a vector. When a wave travels in a positive x- and y-direction with an angle θ from the x-axis, the solution to the wave equation in Equation 8 becomes

$$u(x,y,t) = Ae^{j(\omega t - \vec{k}\cdot\vec{r})} = Ae^{j(\omega t - xk\cos(\theta) - yk\sin(\theta))}. \tag{17}$$

When this wave is travelling in medium 1 and it strikes the boundary with medium 2, that extends itself in the yz-plane, a part of the wave is reflected under an angle θ_r. The relation between the incident and reflected angle is governed by Snell's law of reflection

$$\theta_r = \theta_i, \tag{18}$$

with θ_i the angle of incidence. Another part of the wave is transmitted into medium 2 under an angle θ_t, which is governed by Snell's law of refraction

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{c_1}{c_2} = \frac{k_2}{k_1} \Rightarrow \sin\theta_t = \frac{k_1}{k_2}\sin\theta_i. \tag{19}$$

Both Equation 18 and 19 are solutions of the well-known Snell's relations

$$\frac{\sin\theta_i}{c_1} = \frac{\sin\theta_r}{c_1} = \frac{\sin\theta_t}{c_2}. \tag{20}$$

The refraction and transmission of an incident wave are depicted in Figure 4.

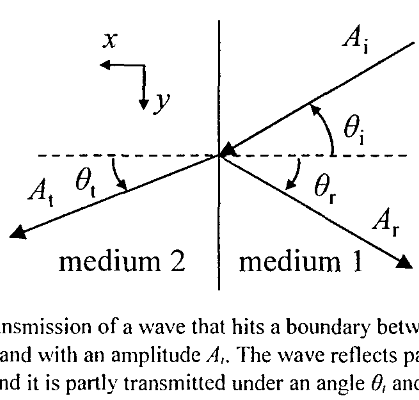

Figure 4 Reflection and transmission of a wave that hits a boundary between medium 1 and medium 2 under an angle θ_i and with an amplitude A_i. The wave reflects partly under an angle θ_r and with an amplitude A_r and it is partly transmitted under an angle θ_t and with an amplitude A_t.

From Equation 19 it follows that

$$\cos\theta_t = \pm\sqrt{1-\sin^2\theta_t} = \pm\sqrt{1-\left(\frac{k_1}{k_2}\right)^2 \sin^2\theta_i}\,. \tag{21}$$

Equation 19 and 21 can be filled in Equation 17 to obtain the wave solution in medium 2. Only the positive solution of Equation 21 results in a physical meaningful wave solution. The amplitudes of the reflected and refracted waves are given by the reflection coefficient Γ and the refraction coefficient τ:

$$\begin{aligned} \Gamma &= \frac{A_r}{A_i} = \frac{c_2\cos\theta_i - c_1\cos\theta_t}{c_2\cos\theta_i + c_1\cos\theta_t} \text{ and} \\ \tau &= \frac{A_t}{A_i} = \frac{2c_2\cos\theta_i}{c_2\cos\theta_i + c_1\cos\theta_t} \text{ with } 1+\Gamma=\tau. \end{aligned} \tag{22}$$

2.5 Surface Waves

An interesting phenomenon occurs when in Equation 21 $k_1 > k_2$; the wave is totally reflected at the boundary, $\sin\theta_t > 1$, and $\cos\theta_t$ becomes imaginary:

$$\cos\theta_t = \pm j\sqrt{\left(\frac{k_1}{k_2}\right)^2 \sin^2\theta_i - 1}\,. \tag{23}$$

When Equation 19 and 23 are substituted in Equation 17, a new wave solution is obtained that equals

$$\begin{aligned} u(x,y,t) &= Ae^{j\left(\omega t + jxk_2\sqrt{\left(\frac{k_1}{k_2}\right)^2 \sin^2\theta_i - 1} - yk_2\frac{k_1}{k_2}\sin\theta_i\right)} \\ &= Ae^{-xk_2\sqrt{\left(\frac{k_1}{k_2}\right)^2 \sin^2\theta_i - 1}}\, e^{j\left(\omega t - y\underbrace{k_1\sin\theta_i}_{k_s}\right)}. \end{aligned} \tag{24}$$

Only the negative solution of Equation 23 is valid. From Equation 24 it becomes clear that a different kind of wave than mentioned before occurs. It travels in the positive y-direction along the boundary. The amplitude of this wave attenuates exponentially in the positive x-direction, creating an evanescent field in medium 2. This kind of wave is called a surface wave or evanescent wave and has a wave number k_s that is smaller than k_1 and larger than k_2. Therefore, the wave propagation velocity of the surface wave is larger than the velocity in medium 1, it is smaller than the velocity in medium 2, and it depends on θ_i [Pain, 1993; Cheng, 1989; Petrashen, 2003].

The theory for surface waves above does not take into account the difference between the wave numbers of shear waves and compression waves. To get a more complete picture the theory can be extended: When either a compression wave or a shear wave is reflected or transmitted, then a part of the wave energy will be converted into a shear or compression wave respectively. Snell's law for an incident longitudinal wave now becomes

$$\frac{\sin\theta_{i,l}}{c_{1,l}} = \frac{\sin\theta_{r,l}}{c_{1,l}} = \frac{\sin\theta_{r,s}}{c_{1,s}} = \frac{\sin\theta_{t,l}}{c_{2,l}} = \frac{\sin\theta_{t,s}}{c_{2,s}}. \tag{25}$$

The second index in $\theta_{x,y}$ indicates whether the angle belongs to a shear (s) or longitudinal (l) wave. From the different propagation velocities it follows that $\theta_{i,l} = \theta_{r,l} > \theta_{r,s}$ and $\theta_{t,l} > \theta_{t,s}$. For an incident shear wave, Snell's law looks very similar:

$$\frac{\sin\theta_{i,s}}{c_{1,s}} = \frac{\sin\theta_{r,l}}{c_{1,l}} = \frac{\sin\theta_{r,s}}{c_{1,s}} = \frac{\sin\theta_{t,l}}{c_{2,l}} = \frac{\sin\theta_{t,s}}{c_{2,s}}. \tag{26}$$

From this equation, it follows that $\theta_{i,s} = \theta_{r,s} < \theta_{r,l}$ and $\theta_{t,l} > \theta_{t,s}$. Shear and longitudinal surface waves occur under the conditions listed in Table 1. From the wave velocities, it follows that a shear surface wave always is accompanied by a compression surface wave. In addition, a shear surface wave is not likely to occur when the incidence wave is a longitudinal wave. Most likely to happen is a longitudinal surface wave when a shear wave was the incident wave [Petrashen, 2003].

Table 1 The conditions for which a longitudinal or shear incident wave results in a longitudinal or shear surface wave. It is always true that $c_{1,l} > c_{1,s}$ and $c_{2,l} > c_{2,s}$ Therefore, when a shear surface wave exists, then a longitudinal surface wave also exists.

		surface wave occurrence	
		longitudinal	shear
incident wave	longitudinal	$\sin\theta_{i,l} > \frac{c_{1,l}}{c_{2,l}}$	$\sin\theta_{i,l} > \frac{c_{1,l}}{c_{2,s}}$
	shear	$\sin\theta_{i,s} > \frac{c_{1,s}}{c_{2,l}}$ or $\sin\theta_{i,s} > \frac{c_{1,s}}{c_{1,l}}$	$\sin\theta_{i,s} > \frac{c_{1,s}}{c_{2,s}}$

2.6 Wave Diffraction

When a small object consisting of medium 2 is embedded in medium 1, waves propagating in medium 1 will tend to bend around the object. This is called diffraction. Diffraction occurs when the size of the object is close to the wavelength of the travelling wave. When the object is smaller, then the wave will not be affected. When the object is larger, then reflection and transmission will occur.

2.7 Finit Sized Vibrators

Imagine that the medium is excited with a finite sized oscillating plate at the upper boundary. Due to its size, the waves created will be neither pure plane waves, nor spherical waves, but somewhere in between. As a result the waves will attenuate more quickly.

When the plate oscillates perpendicular to the surface of the medium, compression waves will travel downwards and shear waves along the surface. However, when the plate oscillates over the surface shear waves will travel downwards and compression waves along the surface (see Figure 5). This will occur especially when the oscillating plate is slightly embedded in the medium.

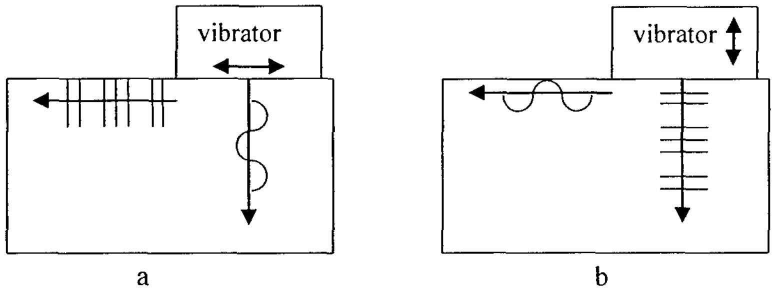

Figure 5 a When the vibrator oscillates horizontally, a shear wave moves downwards and a longitudinal wave propagates along the surface.
b When the vibrator oscillates vertically, a longitudinal wave moves downwards and a shear wave propagates along the surface. A combination of shear and longitudinal waves will occur at different angles.

2.8 Slip

When the oscillating plate vibrates along the surface, shear force is applied to the medium. When the plate is not rigidly attached to the underlying medium slip can occur and wave energy is lost. How easily two materials slip is described by the static friction coefficient μ_s, which depends on the normal force. If the shear force exceeds the static friction coefficient, the material will slip and the friction force will reduce. The friction force is then governed by the kinetic friction coefficient μ_k and the normal force, until the shear velocity becomes zero [Weisstein, 2004a].

3 Structure of the Skin

3.1 Composition

The skin has a thickness range of 0.5 to 6 mm and it is often described as a layered medium of two distinctive layers, the epidermis and the dermis. In the epidermis (75-150 μm thickness), new epidermal cells are continuously formed and transported outwards. On their way, these cells flatten and keratinise; filaments of keratin and links between these filaments are formed and eventually the cells die, leaving a tough, protective layer. The epidermis becomes more dense, stiffer and drier towards the outside.

The dermis (0.6-3 mm thickness) is the thicker layer of the two and it consists mainly of the fibrous proteins collagen, elastin and reticulin. Together they form a complex network filled with fluid. This network embeds blood vessels, nerves, lymphatics, hair follicles, sweat glands and mechanoreceptors. The papillary layer of the dermis lies just under the wavy formed junction between the epidermis and the dermis (the stratum basale) and consists of open networks of fine collagen fibres. Ninety percent of the dermis consists of a denser network of coarse collagen fibres called the reticular layer. This means that the reticular layer is stiffer than the papillary layer. In relaxed skin, the collagen fibres lay in a wave pattern. When the skin is being stretched, at first the collagen fibres will align allowing the skin to be easily stretched. One by one each fibre will stretch, causing a high stiffness [Manschot, 1985; Bischoff, Arruda, & Grosh, 2000]. Under the dermis lies a layer of subcutaneous fat that rests on a stiff layer of muscle or bone.

3.2 Mechanoreceptors

The different types of mechanoreceptors in the skin work together, in order to transmit tactile information to the brain. These mechanoreceptors have different morphologies, functions and locations (see Figure 6). Mechanoreceptors in the human hairy skin show some similar morphological features [Iggo & Andres, 1982]:

- The receptor is formed from the terminal of an afferent that has its cell body in, or near, a dorsal root ganglion or cranial nerve ganglion.
- The receptor terminal shows morphological specialisation: accumulation of mitochondria; presence of granular vesicles; fine filamentous ground substance under the axonal membrane.
- A myelin sheath is absent from the receptor terminal.
- The receptor terminal often is connected to nonneural cells, which may form a complex and characteristic structure in which the nonneural cells can act as a transducer.

Hair follicles are surrounded by mechanoreceptors just below the duct of the sebaceous gland if one is present. There is a difference between the innervations of guard hairs (hairs with large diameter hair shafts) and down hairs (smaller hairs, sometimes minute). Guard hairs are innervated by a collar of lanceolate terminals. Each terminal is lance shaped and sandwiched between two Schwann cells. Small axonal spines protrude from the sharp sides of the lance into the surrounding tissue. The lances are aligned parallel to the long axis of the hair. Together they form a palisade around the hair. Lanceolate terminals are believed to be rapidly adapting [Munger & Ide, 1988; Iggo

et al., 1982]. Several stem axons supply one hair follicle, but one stem axon also supplies several hair follicles [Iggo et al., 1982], causing overlap.
Spiralling around the palisade of lanceolate terminals is the Ruffini terminal. The terminal is not encapsulated by Schwann cells as opposed to Ruffini terminals found in the skin near joints [Munger et al., 1988; Iggo et al., 1982; Hamann, 1995]. To make a distinction between the two types of Ruffini terminals, the naked terminals are called pilo-Ruffini terminals. The Ruffini endings are believed to be slowly adapting receptors [Iggo et al., 1982; Hamann, 1995] and are sensitive to vibrations ranging from 15-400 Hz [Bolanowski, Jr., Gescheider, Verrillo, & Checkosky, 1988; Johansson, Landstrom, & Lundstrom, 1982]. Opposed to guard hairs, down hairs often lack pilo-Ruffini terminals [Munger et al., 1988], but are surrounded by more sensitive lanceolate terminals [Hamann, 1995].
In between hairs clusters of Merkel complexes exist [Munger et al., 1988; Iggo et al., 1982]. They are located at the base of the epidermis and consist of 50 to 70 Merkel complexes in the form of a circular or oval shape with a size of approximately $100 \times 300\ \mu m$. The cluster is supplied by only one axon [Iggo et al., 1982]. The epidermis overlying the cluster is thickened and this dome is called a Haarscheibe. A Merkel complex consists of a disc shaped axon terminal, called a Merkel disc that is in close contact with a special cell, called Merkel cell. The Merkel cell has desmosomes with its adjoining keratinocytes. It is speculated that the Merkel cell communicates with the Merkel disc through synaptic-like junctions. Merkel complexes are categorised as SAI receptors and they are sensitive to perpendicular displacement of the skin [Munger et al., 1988; Iggo et al., 1982; Hamann, 1995]. They are sensitive to vibrations ranging from 0.4-100 Hz [Johansson et al., 1982; Bolanowski, Jr. et al., 1988].
Deeper in the skin, in the dermis, lie the largest, most sensitive and the most extensively investigated mechanoreceptors, called the Pacinian corpuscles. Pacinian corpuscles consist of a myelinated axon with a bare end. This end is enveloped by 20 to 70 densely packed lamellae consisting of an inner and an outer core [Hamann, 1995; Iggo et al., 1982]. The lamellae form a oval shape with a length of 0.5-2 mm and a diameter of 0.7 mm [Iggo et al., 1982; Munger et al., 1988]. The bare axon end has axonal spines of 6 nm that protrude between the layers of the inner lamellae, very much like the axonal spines found in lanceolate terminals. The Pacinian corpuscles are rapidly adapting and are sensitive to vibrations from approximately 80 to 300 Hz [Hamann, 1995; Iggo et al., 1982; Munger et al., 1988; Bolanowski, Jr. et al., 1988; Johansson et al., 1982]. It is believed that slip in the lamellae is partly responsible for the high-pass properties of the mechanoreceptor [Munger et al., 1988; Hamann, 1995; Sherwood, 1997].
In great abundance in the skin are the free nerve endings. These are small nerve fibres without specialised nerve endings. Some of them are capable of detecting mechanical stimuli. They might give a tickling sensation when stimulated [Hamann, 1995]. The well known Meissner corpuscles are not present in hairy skin.

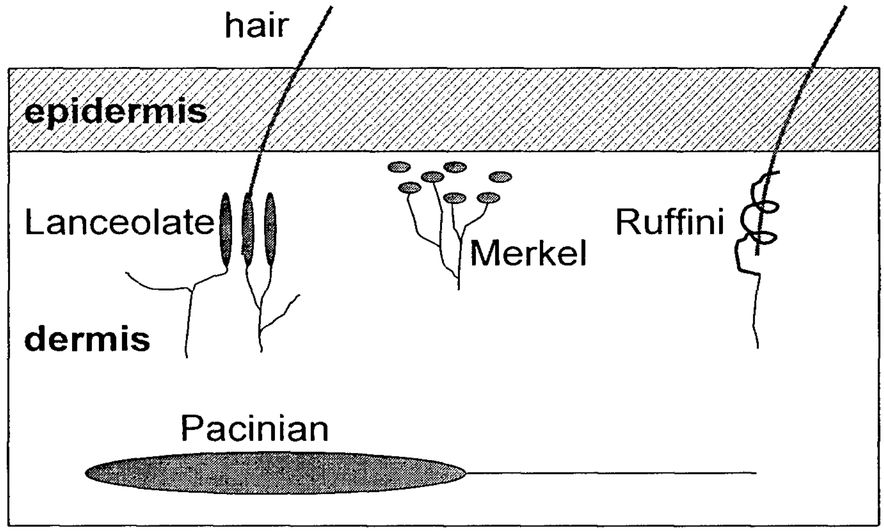

Figure 6 Schematic representation of the distribution of mechanoreceptors in the hairy skin. Shown are lanceolate terminals, pilo-Ruffini terminals, Merkel complexes, and Pacinian corpuscles.

3.3 Mechanotransduction of Vibrations

Mechanotransduction describes the process needed for the conversion of mechanical stimuli into a bursts of action potentials. It can be viewed as a three-stage process [French, 1992]: firstly, the stimulus is mechanically coupled to the receptor. Some responsible structures already mentioned above are hairs, lamellae, axonal spines, and the epidermis. These structures attenuate or amplify the stimulus, acting like a specific filter. Membrane penetrating proteins may have a function in mechanotransduction. An important family of proteins could be degenerin/epithelial Na^+ channel proteins [Welsh, Price, & Xie, 2002].

Secondly, the deformation of the receptor is converted into an electrical signal by mechanically sensitive ion channels. These channels appear to be tension sensitive [French, 1992]. Interesting are the results of experiments Hamill performed on mechanosensitive, nonsensory frog oocytes (eggs) [Hamill & McBride, 1995]. Hamill applied suction to the cell membranes of the oocytes and measured the resulting change in membrane current with a patch clamp. When a pressure ramp was applied on a piece of membrane containing only one channel, the membrane current showed a step response. When more channels were involved the current increased with increasing pressure and saturated before the maximum pressure was reached. Hamill concluded from this that channels are either fully opened or closed and that each channel opens at a different pressure. He also applied a step stimulus and measured the adaptation of multiple channels and single channels. It turned out that each channel had a different adaptation time, resulting in exponential adaptation for a group of channels. Remarkably, adapted channels could be reactivated by further increasing the pressure.

Thirdly, the graded potential (depolarisation) caused by the influx and efflux of ions has to lead to action potentials. When the membrane potential in the axon near the receptor reaches a threshold potential, voltage controlled ion gates open and a sudden influx of Na^+ occurs resulting in a sharp increase of the local membrane potential (depolarisation). The Na^+ influx is rapidly followed by an efflux of K^+, resulting in a sharp decrease of the membrane potential (repolarisation). Together they form the potential peak characteristic for the action potential [Sherwood, 1997]. Several mechanisms can influence the graded potential to action potential encoding, which are described by French [Welsh et al., 2002].

3.4 Wave Propagation Models for the Skin

In the literature, several mechanical models of skin have been described. Usually they describe the skin as being composed of one to three layers of materials with different mechanical properties. Below some models and results are described. Mechanical parameters are listed when relevant or present.
Sherrick and Cholewiak describe the skin as a 'semi plastic membrane that overlays a viscoelastic substrate that varies greatly in local density, hardness, and other physical properties'. On the skin surface, mechanical disturbances propagate as a continually damped wave, which attenuates following the inverse-square law. The surface wave is generated by a combination of shear and compression waves within the substrate [Sherrick & Cholewiak, 1986].
Von Gierke et al. recognised three types of waves that propagate through the skin: compression waves, shear waves and surface waves. According to Von Gierke shear waves attenuate much faster in the skin than compression waves. As a model, he used a vibrating rigid sphere in an unlimited, homogeneous, viscous, elastic, compressible medium. The parameter values he has used are listed in Table 2. Note that the imaginary parts of the Lamé constants are linearly dependent on the frequency [von Gierke, Oestereicher, Franke, Parrack, & von Wittern, 1952].

Table 2 Mechanical parameter values as used by Von Gierke [von Gierke et al., 1952].

ρ	$\mu = \mu' + j\omega\mu''$		$\lambda = \lambda' + j\omega\lambda''$	
	μ'	μ''	λ'	λ''
kg/m^3	Pa	Pa·s	Pa	Pa·s
$1.1 \cdot 10^3$	$2.5 \cdot 10^3$	15	$2.6 \cdot 10^9$	0

Ashby et al. list some mechanical properties for a large number of natural materials. These natural materials also include skin. For the skin they had taken $\rho = 1.3 \cdot 10^3$ kg/m^3 and $E = 40 \cdot 10^6$ Pa [Ashby, Gibson, Wegst, & Olive, 1995].
Van Doren modelled the skin of the fingertip as a slab of homogeneous, isotropic, viscoelastic material with the material properties listed in Table 3. The slap was rigidly connected to the ground. He measured the spatiotemporal sensitivity at two temporal frequencies (8 Hz and 128 Hz) and twelve spatial frequencies ranging from 0.0-1.03 cycles/mm. The results showed a decrease in the sensitivity with increasing spatial frequency for 128 Hz, and an increase in sensitivity for 8 Hz. He assumed that the psychophysical threshold of a receptor type corresponds to a constant value of one strain component evaluated at the location of the appropriate receptor. He used the model of the skin and the measurements to obtain this strain component and the location of the mechanoreceptor in the skin. The measurements were also used to estimate the skin thickness in the model [Doren, 1989].

Table 3 Mechanical parameter values as used by Van Doren [Doren, 1989].

Medium index	Layer thickness	ρ	$\mu = \mu' + j\omega\mu''$		λ
			μ'	μ''	
	m	kg/m^3	Pa	Pa.s	Pa
1	$4.96 \cdot 10^{-3}$	$1.1 \cdot 10^3$	$2.5 \cdot 10^4$	40	∞

Klochkov modelled the skin as a two-layer medium. The first layer has a thickness that is varied. The second layer extends into infinity. He had positioned a surface source of forced vibration on top of the first layer, capable of normal and tangential oscillations. For normal displacement, the frequency dependency was calculated. It appeared that the resonance frequency increased with a decrease in the layer thickness and that the resonance peak became lower and wider. The resonance frequencies ranged from 50 to 300 Hz. In the case of tangential displacement, two resonance frequencies exist with a dip in between. For layer thicknesses larger than 2 cm the amplitude of the dip became less and its frequency shifted to lower values. For layer thicknesses smaller than 2 cm the frequency of the dip shifted to higher values and the amplitude decreased. In the case of a layer thickness of 2 cm the two resonance frequencies were approximately 45 and 90 Hz. The dip occurred at 56 Hz. Klochov also calculated the two dimensional (along the surface and in the depth of the tissue) spatial distribution of the amplitude of the displacement for both tangential and normal oscillations. The oscillation frequency was set to 70 Hz. The results showed that in the case of normal oscillation the waves damped out quickly in both dimensions: within 5 cm along the surface, and within 3 cm in the depth. Tangential oscillation resulted in a more complex distribution that showed less attenuation [Klochkov, 2002].

Table 4 Mechanical parameter values as used by Klochkov [Klochkov, 2002].

Medium index	Layer thickness	ρ	$\mu = \mu' + j\omega\mu''$		λ
			μ'	μ''	
	m	kg/m^3	Pa	Pa.s	Pa
1	$0.3\text{-}4 \cdot 10^{-2}$	$1.05 \cdot 10^3$	$5 \cdot 10^3$	2.5	$2.67 \cdot 10^9$
2	∞	$1.6 \cdot 10^3$	$6.4 \cdot 10^9$	0	$5.7 \cdot 10^9$

Pereira modelled the skin as a material with three layers: the stratum corneum, the dermis, and the subcutaneous fat. On top of the stratum corneum, he placed a tangentially oscillating line source. He varied the shear modulus and the loss modulus, while measuring the surface wave velocity. Note that the loss modulus is independent of the frequency. Pereira concluded that the stiffness of the stratum corneum had a large influence on the propagation velocity of surface waves [Pereira, Mansour, & Davis, 1991].

Table 5 Mechanical parameter values as used by Pereira [Pereira et al., 1991]. Medium 1 is the stratum corneum, medium 2 is the dermis, and medium 3 is subcutaneous fat.

Medium index	Layer thickness	ρ	$\mu = \mu' + j\mu''$	
			μ'	μ''
	m	kg/m^3	Pa	Pa
1	$15 \cdot 10^{-6}$	$1 \cdot 10^3$	$10 \cdot 10^4 \cdot \mu_2$	0.25-0.75.μ_1
2	$15 \cdot 10^{-3}$	$1 \cdot 10^3$	$60 \cdot 10^3$	$32.5 \cdot 10^3$
3	∞	$0.9 \cdot 10^3$	$20 \cdot 10^3$	10.10^3

Timanin also used a three-layered model with a vibrating pressure source on top. He used excitation frequencies ranging from 20 to 60 Hz. Lower frequencies resulted in less attenuation. The displacement amplitude at a fixed point increased with the radius of the pressure source [Timanin, 2002].

Table 6 Mechanical parameter values as used by Timanin [Timanin, 2002]. The λ's have been estimated using the given longitudinal wave propagation velocities c_l.

Medium index	Layer thickness	ρ	$\mu = \mu' + j\omega\mu''$		c_l	$\lambda = c_l^2 \rho - 2\mu'$
			μ'	μ''		
	m	kg/m^3	Pa	Pa.s	m/s	Pa
1	$5 \cdot 10^{-3}$	930	$1 \cdot 10^3$	6	1450	$1.96 \cdot 10^9$
2	$10 \cdot 10^{-3}$	1040	$4 \cdot 10^3$	3	1570	$2.56 \cdot 10^9$
3	∞	1080	$1.7 \cdot 10^9$	2	1574	$0.98 \cdot 10^9$

4 Design Criteria

The knowledge from the previous two chapters can be used to design a tactile display that is capable of precise, local skin stimulation. In this chapter some design criteria are composed. For this purpose the tactile display has been divided into three parts: the tactor, the tactor-skin interface, and the part that holds the tactors, which has been labelled as the tactor carrier. For each of these parts criteria listed below.

4.1 Tactor

The correct answer to the question: 'Which type of mechanoreceptor is stimulated by mechanical stimulation on the surface of the skin?' is: all types. How it is perceived depends on the location, sensitivity, density and the type of innervation of a type of mechanoreceptor. Mechanoreceptors located near the surface are subjected to a larger wave amplitude then the more deeply located mechanoreceptors. Considering this, the Pacinian corpuscles have a disadvantage here, because they are located deeply in the skin. In addition the density of Pacinian corpuscles in the skin is very low. However, they are believed to be very sensitive, because they are large and have many layers that effectively transfer vibration energy to the axonal spikes. Mechanoreceptors that are located near the surface and that are densely packed in the skin are the clusters of Merkel complexes in between hairs. The localisation of a stimulus might not be very good, because each cluster is supplied by only one axon, whereas one Pacinian corpuscle is connected to a single axon. A more promising innervation have the lanceolate terminals in hair follicles; one hair follicle is supplied by more than one nerve fibre. Pilo-Ruffini endings probably also play a mayor role in the detection of vibration stimuli on locations where guard hairs grow. It is expected that mechanoreceptors are best stimulated by shear waves, because according to Equation 9 shear waves exert a local force difference on two neighbouring particles that is approximately a thousand times larger. Consequently, shear stimulation of the skin results in more local stress in the mechanoreceptors; the receptor is stretched and compressed instead of pushed forwards and backwards when a wave passes. However, a vibrator that oscillates along the surface of the skin slips more easily than a vibrator that oscillates perpendicular. This results in a less efficient transfer of the vibration energy. Vibrators that are used in a tactile display often do not have a clear oscillation direction and will evoke a mixture of longitudinal and shear waves with varying polarisations.

Since the epidermis is stiffer than the dermis, the waves will propagate farther in the epidermis parallel to the surface of the skin. According to Equation 15, shear and longitudinal waves will most likely penetrate through the dermis and the subcutaneous fat layer and reflect almost entirely on the much stiffer, underlying layer that consists of muscle or bone. The reflected waves arrive at the epidermis-air boundary under every possible angle, because of the spherical like form of the waves. The propagation velocity of longitudinal waves in air is smaller than the velocity in skin and shear waves cannot exist in air. Therefore, according to Table 1 only longitudinal surface waves that originate from shear waves can exist. Perpendicular excitation of the skin would of course result in a shear wave travelling along the surface of the skin starting at the rim of the source, because of the up and down motion of the skin. In the case of parallel excitation, a longitudinal wave would travel along the surface (see Figure 5).

The attenuation of waves in the skin depends on the loss modulus μ'' and is governed by Equation 13. This attenuation increases with the vibration frequency. From

Table 2-6 it becomes clear that λ for the dermis is a factor 10^6 larger than μ', which results in a much smaller attenuation for longitudinal waves than for shear waves. It can be calculated that a 100 Hz plane shear wave has to travel approximately 4 cm in the dermis to become a factor **e** smaller. Given that the thickness of the skin is often less then 6 mm and that in general tactors are relatively large compared to the thickness of the skin, it can be concluded that directly underneath a tactor at a wave frequency of 100 Hz mechanoreceptors experience almost the same wave amplitude.
Diffraction could cause high attenuation of waves, because of increased path lengths and complicated interference patterns. However, the propagation velocity of shear waves in the dermis will be approximately $c_s \approx 2\ \mathrm{m/s}$ and the wavelength at 100 Hz will be approximately 2 cm (for longitudinal waves they are both approximately a thousand times larger). Structures in the skin like cells, nerves, vessels, hair follicles and glands are much smaller than that. Therefore, shear waves and certainly longitudinal waves will not diffract in the skin. When the wave frequency is high enough ($f >> 100\ \mathrm{Hz}$) scattering will occur. However, these frequencies lie above the frequencies that can be perceived by the mechanoreceptors in the human skin.
Waves with wave frequencies larger than 100 Hz will not stimulate the slowly adapting Merkel cells, but they will stimulate the very sensitive Pacinian corpuscles. Furthermore, they dampen out more quickly along the surface of the skin then slowly oscillating waves. Although vibrators often will use more energy when operating at higher frequencies, it is preferable to use a stimulation frequency of 200 Hz (within the frequency range in which Pacinian corpuscles are the most sensitive).

Table 7 Summary of the design criteria for the tactor.

Design criteria for the tactor
When no slip across the skin can occur, use a tactor that oscillates parallel to the skin for better stimulation of the mechanoreceptors. Otherwise use perpendicular stimulation.
Use a stimulation frequency of 200 Hz

4.2 Tactor-Skin Interface

The interface between the tactor and the skin should be designed such that the transfer of vibration energy from the tactor to the skin is large. A well designed contact will reduce the need for strong vibrators that have high energy consumption.
Equation 16 tells us to insert a material between the vibrator and the skin with an impedance that equals $\sqrt{Z_1 Z_2}$ and a thickness of $\lambda/4$. A perfect match is not feasible in the case of longitudinal waves, because its wavelength in solid materials is meters long. For shear waves, the matching of impedances will be easier. However, the impedance of the skin varies with the location on the skin so the match will never be perfect.
Another way to improve the transfer of wave energy is achieved by gluing the tactor to the skin. This will give the highest friction between the tactor and the skin. Often it will be impractical to attach the vibrator rigidly to the skin. In that case, the vibrator will be pressed onto the skin with or without a material like clothing in-between. In the first case, the vibrator should have enough static friction or else it will slip. In the latter case, it is expected that the fibres in clothes slip easily and reduce the energy transfer. With simulation, it should be possible to predict the influence of different types of clothing between the tactor and the skin. Mechanical properties of common textiles are listed in Appendix A.

The friction between the tactor and the skin can also be increased by applying more pressure on the tactor. However, this will stretch the skin and since it is a nonlinear material, it becomes stiffer when it is stretched (larger μ'). This is caused by the mechanical properties of collagen networks. In a stiffer material, there will be less attenuation of waves and a higher wave propagation velocity. Skin stretch can also occur during body movement or during contact with objects in the environment or during stimulations with large amplitudes. To keep a constant sensation, the amplitude of pressure fluctuation have to be reduced. This could be accomplished by letting the force act on a large surface.
The interface between the tactor and the skin also plays a role in localising the vibrations in the skin; All waves will attenuate with the distance from the source, obeying approximately Equation 10. When the contact area between the vibration source and the skin is large, the waves will behave more like plane waves. When it is small, the wave will behave more like spherical waves. Consequently, vibrations originating from a small contact area will dampen more quickly than waves originating from a large contact area. A small contact area is preferable, since it reduces the spreading of the vibrations. It also reduces the need for strong vibrators, because less skin mass has to be moved.

Table 8 Summary of the design criteria for the tactor-skin interface.

Design criteria for the tactor-skin interface
Glue the tactor to the skin, or coat the tactor with a material that does not slip easily to prevent slip
Keep the tactor-skin contact area small in order to keep the vibrations local
Insert material of thickness λ/4 between the tactor and the skin (if possible) to obtain a good transfer of vibration energy

4.3 Tactor Carrier

In the current version of the tactile vest columns tactors are attached to strips of Velcro. When one tactor in a column is activated, waves propagate along the strip of stiff Velcro. These waves transfer energy to other tactors and introduce tactile noise in the skin. A vibrator can be isolated from its carrier by embedding it in a soft material with an impedance that greatly differs from the impedance of the vibrator, which on its turn is surrounded by another dense material. This second layer causes the vibration to be reflected back to the source. Care should be taken that vibrations do not leak to the bulk material via the skin (see Figure 7). Fixation of the skin just around the vibrator will damp the waves travelling on and near the surface of the skin, but not the waves deeper below the surface. Electric wires can also create vibration leaks.

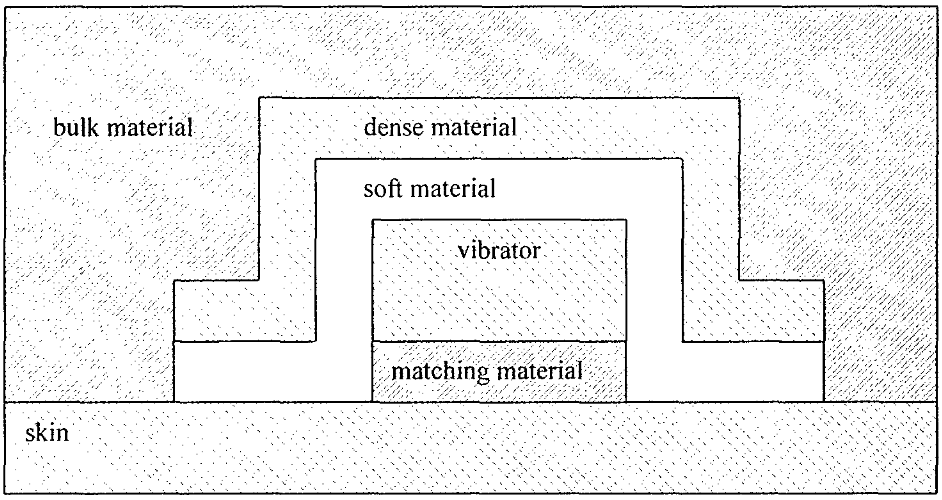

Figure 7 Proposal for embedding of the vibrator. The transfer of vibration energy from the vibrator to the skin is maximized by the addition of an extra layer of material, called the matching material. The transfer of vibration energy from the vibrator to the bulk material is minimised by a layer of soft material followed by a layer of dense material.

In some user environments, a low noise emission is important. The amount of noise produced by a vibrator depends on the transfer of vibration energy to the air. The isolation of the vibrator from the bulk material mentioned above reduces this transfer. In general, the size of the vibrating surfaces should be kept as small as possible.

Table 9 Summary of the design criteria for the tactor carrier.

Design criteria for the tactor carrier
Keep the size of vibrating surfaces as small to reduce noise
Pack the vibrator in isolating material to prevent spreading of the vibrations through the tactor carrier
Do not attach the tactors directly to dense materials in the tactor carrier

5 References

Ashby, M. F., Gibson, L. J., Wegst, U., & Olive, R. (1995). The mechanical properties of natural materials. I. Material property charts. *Proc.R.Soc.Lond.A, 450,* 123-140.

Bischoff, J. E., Arruda, E. M., & Grosh, K. (2000). Finite element modeling of human skin using an isotropic, nonlinear elastic constitutive model. *Journal of Biomechanics, 33,* 645-652.

Bolanowski, S. J., Jr., Gescheider, G. A., Verrillo, R. T., & Checkosky, C. M. (1988). Four channels mediate the mechanical aspects of touch. *J.Acoust.Soc.Am., 84,* 1680-1694.

Cheng, D. K. (1989). *Field and Wave Electromagnetics.* (2nd ed.) New York: Addison-Wesley Publishing Company, Inc.

Doren, C. L. v. (1989). A model of spatiotemporal tactile sensitivity linking psychophysics to tissue mechanics. *J.Acoust.Soc.Am., 85,* 2065-2080.

Feynman, R. P., Leighton, R. B., & Sands, M. (1977). *The Feynman Lectures On Physics.* (6th ed.) (vol. 2) Massachusetts: Addison-Wesley Publishing Company.

French, A. S. (1992). Mechanotransduction. *Annual Review of Physiology, 54,* 135-152.

Hamann, W. (1995). Mammalian Cutaneous Mechanoreceptors. *Progress in Biophysics and Molecular Biology, 64,* 81-104.

Hamill, O. P. & McBride, D. W. jr. (1995). Mechanoreceptive Membrane Channels: Mechanically sensitive membrane channels may participate in processes as diverse as volume regulation in cells and sound reception in vertebrates. *American Scientist, 83,* 30-37.

Iggo, A. & Andres, K. H. (1982). Morphology of Cutaneous Receptors. *Ann.Rev.Neurosci., 5,* 1-31.

Johansson, S. R., Landstrom, U., & Lundstrom, R. (1982). Responses of mechanoreceptive afferent units in the glabrous skin of the human hand to sinusoidal skin displacements. *Brain Research, 244,* 17-25.

Klochkov, B. N. (2002). Near Field of a Low-Frequency Source of Forced Vibration on a Layered Biological Tissue. *Acoustical Physics, 58,* 70-76.

Leijendeckers, P. P. H., Fortuin, J. B., van Herwijnen, F., & Leegwater, H. (1998). *PolyTechnisch zakboekje.* (48th ed.) Arnhem, The Netherlands: Koninklijke PBNA.

Main, I. G. (1993). *Vibrations and Waves in Physics.* (3rd ed.) Cambridge: Cambridge University Press.

Manschot, J. F. M. (1985). *The Mechanical Properties of Human Skin in Vivo.* M.Sc. Thesis, Katholieke Universiteit Nijmegen.

Munger, B. L. & Ide, C. (1988). The Structure and Function of Cutaneous Sensory Receptors. *Arch.Histol.Cytol., 51,* 1-34.

Pain, H. J. (1993). *The Physics of Vibrations and Waves.* (4th ed.) Chichester: John Wiley & Sons Ltd.

Pereira, J. M., Mansour, J. M., & Davis, B. R. (1991). The Effects of Layer Properties on Shear Disturbance Propagation in Skin. *Transactions of the ASME, 113,* 30-35.

Petrashen, G. I. (2003). Propagation of Seismic Wave Fields in Layered Media. II. *Journal of Mathematical Sciences, 117,* 3805-3872.

Sherrick, C. E. & Cholewiak, R. W. (1986). Cutaneous Sensitivity. In K.R.Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of Perception and Human Performance* (pp. 12-1-12-58). USA: John Wiley & Sons, Inc.

Sherwood, L. (1997). *Human Physiology: from cells to systems.* (3rd ed.) Belmont, USA: West Publishing Company.

Timanin, E. M. (2002). Displacement Field Produced by a Surface Source of Vibrations in a Layered Biological Tissue. *Acoustical Physics, 48,* 87-93.

Van Erp, J. B. F., Jansen, C., Dobbins, T., & Van Veen, H. A. H. C. (2004). Vibrotactile Waypoint Navigation at Sea and in the Air: two Case Studies. In M. Buss & M. Fritschi (Eds.), *Proceedings of the 4th International Conference Eurohaptics 2004* (pp. 166-173). München, Germany: Herbert Hieronymus.

Van Erp, J. B. F. & Van Veen, H. A. H. C. (2003). A Multi-purpose Tactile Vest for Astronauts in the International Space Station. In (pp. 405-408).

Van Erp, J. B. F., Veltman, J. A., Van Veen, H. A. H. C., & Oving, A. B. (2002). *Een tactiel vest vermindert drift bij hoveren* (Rep. No. TM 02 A041).

Van Veen, H. A. H. C., Spapé, M., & Van Erp, J. B. F. (2004). Waypoint Navigation on Land: Different Ways of Coding Distance to the Next Waypoint. In M. Buss & M. Fritschi (Eds.), *Proceedings of the 4th International Conference Eurohaptics 2004* (pp. 160-165). München, Germany: Herbert Hieronymus.

Van Veen, H. A. H. C. & Van Erp, J. B. F. (2003). Providing Directional Information with Tactile Torso Displays. In.

von Gierke, H. E., Oestereicher, H. L., Franke, E. K., Parrack, H. O., & von Wittern, W. W. (1952). Physics of Vibrations in Living Tissue. *J.Appl.Physiol., 4,* 886-900.

Weisstein, E. W. (2004a), (2004b) and (2004c). Eric Weisstein's World of Physics. http://scienceworld.wolfram.com/physics/ [On-line]. Available: http://scienceworld.wolfram.com/physics/

Welsh, M. J., Price, M. P., & Xie, J. (2002). Biochemical Basis of Touch Perception: Mechanosensory Function of Degenerin/Epithelial Na+ Channels. *The Journal of Biological Chemistry, 277,* 2369-2372.

Yerges, L. F. (1969). *Sound, Noise, and Vibration Control.* New York: Van Nostrand Reinhold Company.

6 Signature

Soesterberg, September 2005

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A Mechanical Properties of Materials

In this appendix mechanical properties of the skin and common clothing are given, in case future tactile systems are going to be modelled with for instance finite element (FEM) models.
Unfortunately, it was not possible to find mechanical properties of viscoelastic skin, therefore estimations have been made from Table 2-6.

Table A.1 Ranges of the mechanical properties of human skin estimated from Table 2-6.

Material name	Density	Shear elasticity	Shear viscosity	Volume compres-sibility	Volume viscosity
	ρ kg/m³ ·10³	μ' Pa ·10³	μ" Pa·s	λ' Pa ·10⁹	λ" Pa·s
epidermis	0.9-1.0	1.0	6	2.0	0
dermis	1.0-1.1	2.5-5	2.5-40	2.6	0
Subcuta-neous fat	1.1	1.7	2	1.0	0

In the textile industry the Kawabata test method is used to obtain mechanical parameters. Unfortunately, these parameters are not clearly related to the parameters used in this document. Important Kawabata parameters are the fabric weight per unit area (W), the fabric thickness (T_0) and the tensile energy (WT). WT is defined as the area under the stress-strain curve from 0 to maximum strain (maximum stress equals $4.9\ \mathrm{N/cm}$). Also important is the linearity of load-extension curve (LT), which is defined as

$$LT = \frac{WT}{\frac{1}{2}\left(\max(\varepsilon)\cdot\max(\sigma)\right)}. \qquad \text{(A1)}$$

Other parameters are the compressional energy (WC) and the linearity of the compression thickness curve (LC). They are similar to WT and LT. The maximum stress in the stress-strain curve equals $0.49\ \mathrm{N/cm^2}$. Another important parameter is the shear rigidity (G) along the surface obtained from the shear stress versus the shear angle curve. This curve is measured by shearing a textile sample of dimensions 5 by 20 cm parallel to its long axis, while keeping a constant tension of $98.1\ \mathrm{mN/cm}$. The parameter $2HG$ gives the hysteresis width of this curve at the shear angle of 0.5 degrees.
Obviously, W is related to ρ. It might be possible to make estimations of the Young's moduli at zero strain along the surface of the textile and perpendicular to the surface of the textile from the parameters WT, LT, WC, and LC:

$$\hat{E}\Big|_{\varepsilon=0} = LT^2 \cdot \frac{\max(\sigma)^2}{2\cdot WT}, \qquad \text{(A2)}$$

in which $\hat{E}\Big|_{\varepsilon=0}$ is the estimated Young's modulus around zero strain. LT and WT can be replaced by LC and WC respectively.

The parameter G might be used to estimate the shear modulus and the imaginary part of the shear modulus might be (only partially) obtained from $2HG$. Ranges of values for the parameters mentioned above are listed in Table A.2.

Table A.2 Ranges of values of the Kawabata parameters for common textiles.

Parameter name	Value	
W	60-525	g/m^2
T_0	0.4-3.1	mm
WT	5-50	J/m
LT	0.3-0.95	
WC	0.15-2.5	J/m^2
LC	0.3-0.7	
G	0.5-8.0	N/m°
2HG	3-20	N/m

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REPORT DOCUMENTATION PAGE
(MOD-NL)

1. DEFENCE REPORT NO (MOD-NL)	2. RECIPIENT'S ACCESSION NO	3. PERFORMING ORGANIZATION REPORT NO
TD2005-075		TNO-DV3 2005 A075
4. PROJECT/TASK/WORK UNIT NO	**5. CONTRACT NO**	**6. REPORT DATE**
013.44436	-	September 2005
7. NUMBER OF PAGES	**8. NUMBER OF REFERENCES**	**9. TYPE OF REPORT AND DATES COVERED**
31 (incl 1 appendix, excl RDP & distribution list)	33	Final

10. TITLE AND SUBTITLE

Tactile Displays and Elastic Waves

11. AUTHOR(S)

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12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Kampweg 5, Soesterberg, The Netherlands

13. SPONSORING AGENCY NAME(S) AND ADDRESS(ES)

Klu, Vlb 5B, Tactische helicoptergroep, P.O. Box 160 3769 ZK Soesterberg, The Netherlands

14. SUPPLEMENTARY NOTES

The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

When tactors of a tactile display are mounted in a tactor carrier, e.g. a vest or a chair, vibrations will spread out through the skin and the carrier. Vibrations should be local to ensure good detection; spreading through the skin or the environment has to be minimised.
A literature study has been done to obtain the following design criteria: Tactors should oscillate parallel to the skin at a frequency of 200 Hz. Tactors should be glued to the skin or coated with a material that does not slip easily. When the tactors cannot be attached free of slip, use tactors that oscillate perpendicular to the skin. The size of the contact area between the tactor and the skin should be small. Soft material encased in stiff material should be used between the tactor carrier and the tactor in order to reduce the amount of vibration energy emitted to the tactor carrier and to reflect energy to the skin.

16. DESCRIPTORS	IDENTIFIERS
Tactile Displays Wave propagation Vibrations Skin	

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
Ongerubriceerd	Ongerubriceerd	Ongerubriceerd

18. DISTRIBUTION AVAILABILITY STATEMENT	17d. SECURITY CLASSIFICATION (OF TITLES
Unlimited Distribution	Ongerubriceerd

Distributionlist

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