Stimuler le toucher par vibrations

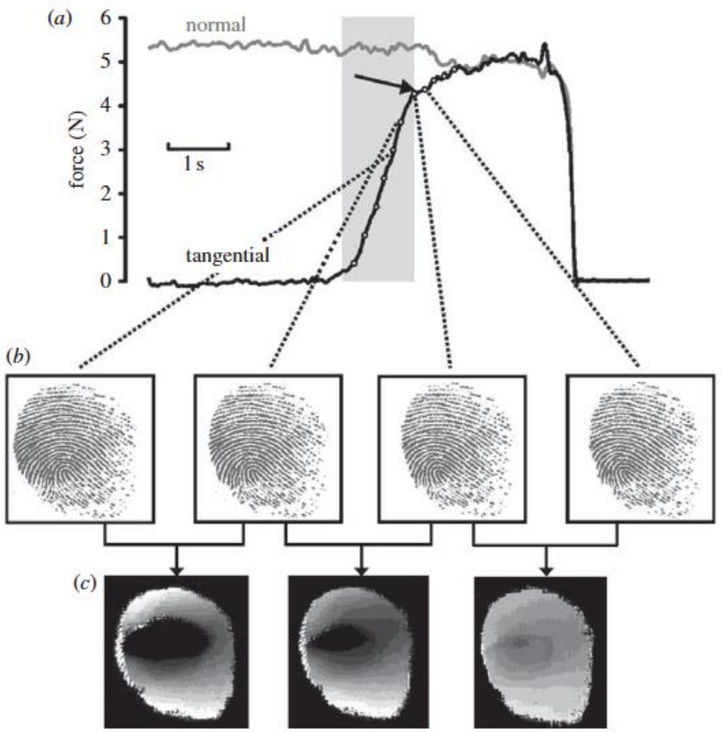
Principes physiques des stimulateurs tactiles

Charles Hudin – Ingénieur chercheur CEA

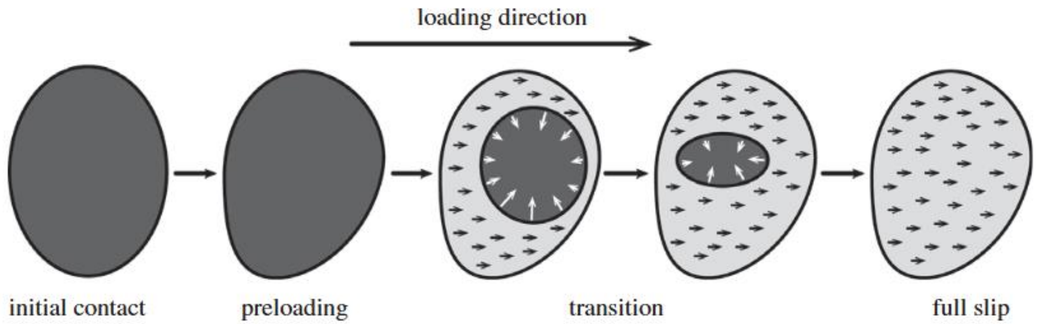
Stimuler le(s) toucher(s)

- Lequel ?
  - Sens Kinesthésique
    - Perception des efforts et des mouvements du corps
  - Sens tactile
    - Perception cutanée des forces et déformations
    - Perception de la douleur
    - Perception de la chaleur
- Pourquoi ?
  - Communiquer une information
  - Simuler le contact et l'interaction avec une surface/un objet

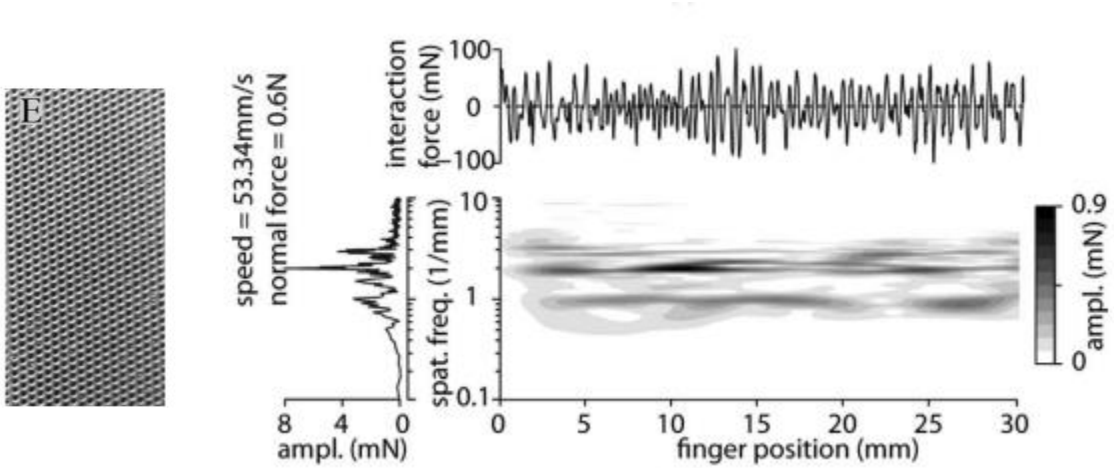
Simuler l’interaction avec une surface



Adams et al., « Finger pad friction and its role in grip and touch », in *J. R. Soc. Interface.* 2013

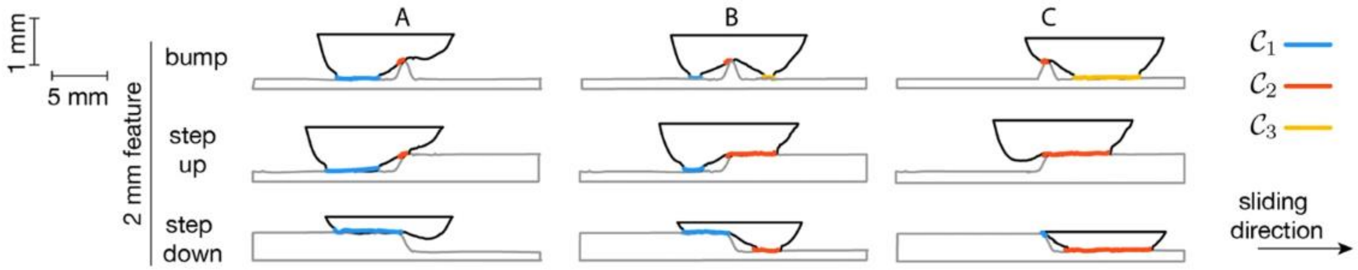


André et al., “Effect of skin hydration on the dynamics of fingertip gripping contact” in J. R. Soc. Interface, 2011

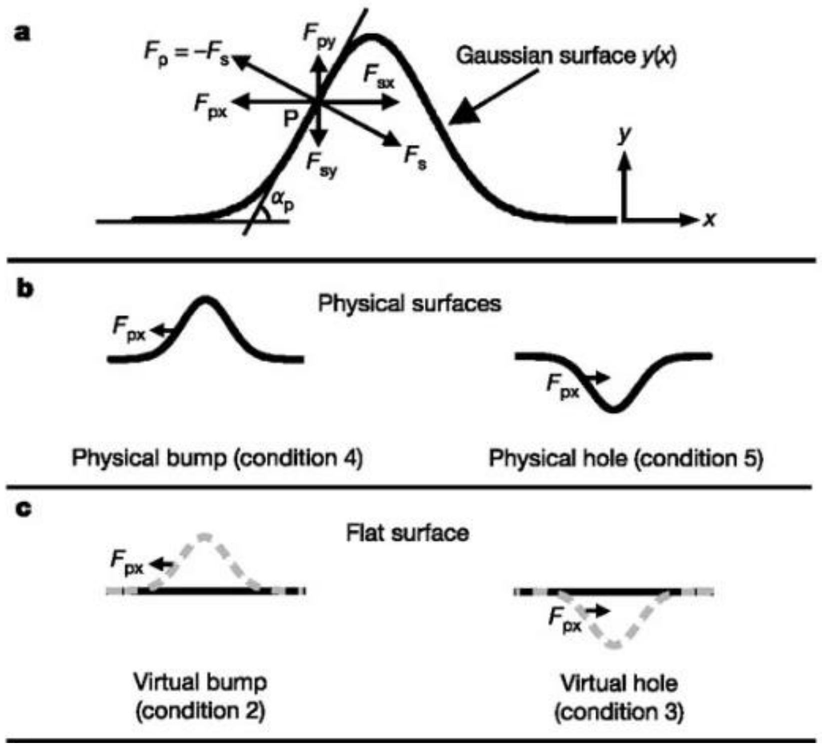


Wiertlewski et al. "The Spatial Spectrum of Tangential Skin Displacement Can Encode Tactual Texture," in *IEEE Trans. on Robotics*, 2011

Simuler l'interaction avec une surface



Janko et al., Contact geometry and mechanics predict friction forces during tactile surface exploration. *Sci Rep* **8**, 4868 (2018).



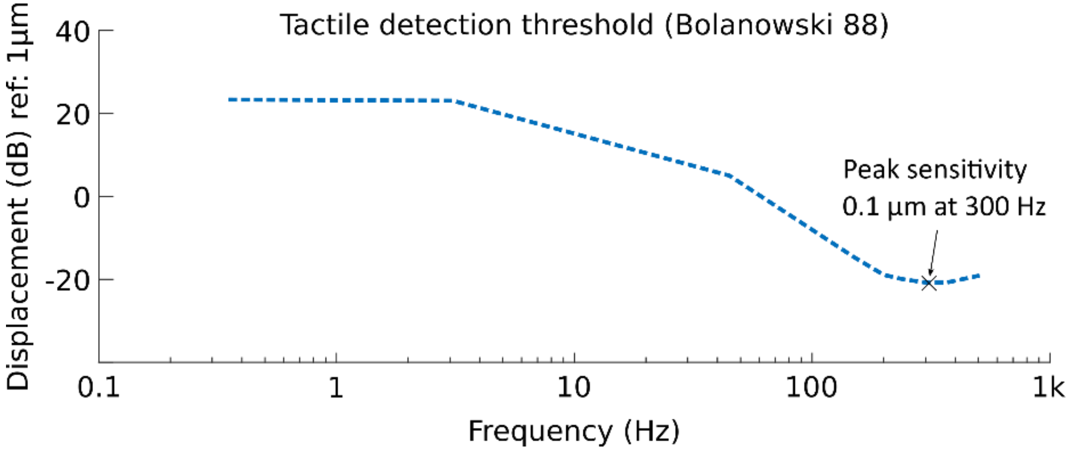
Robles-De-La-Torre and Hayward. "Force can overcome object geometry in the perception of shape through active touch". *Nature* **412**, 445–448 (2001)

Deux contributions à la perception des textures (Katz)

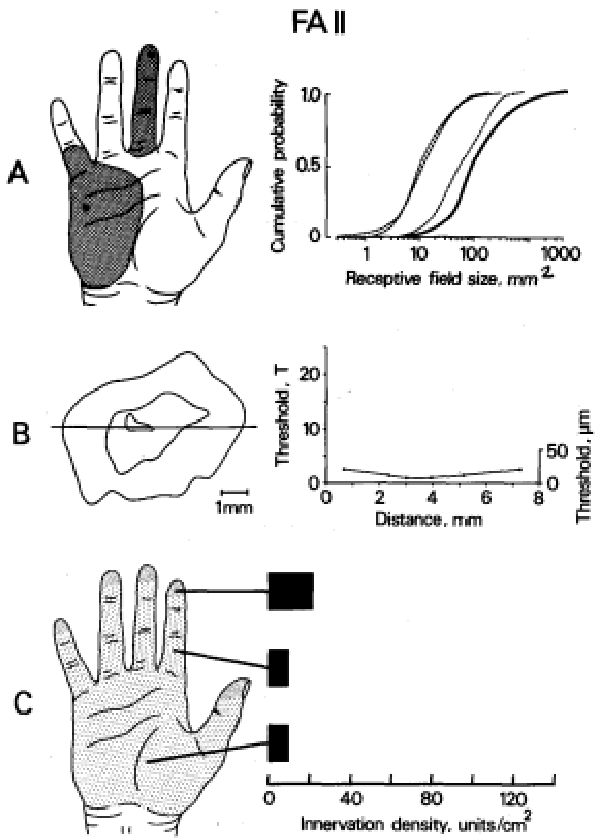
- Contribution spatiale du profil de la surface à large échelle (>100 µm).
- Contribution temporelle des vibrations produites par le glissement sur les aspérités fines (<100 µm).

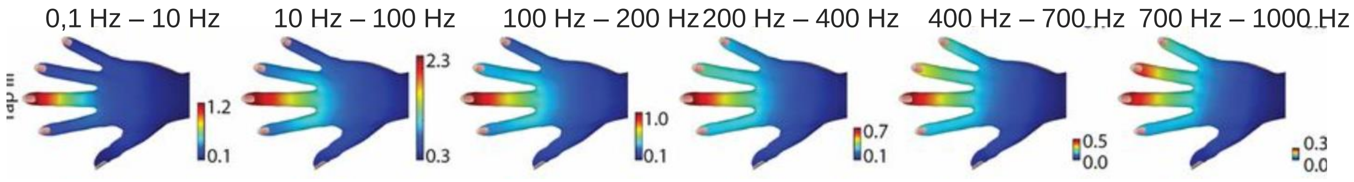
Stimulation vibrotactile

Physiologie



Bolanowski et al., Four channels mediate the mechanical aspects of touch. J Acoust Soc Am. 1988



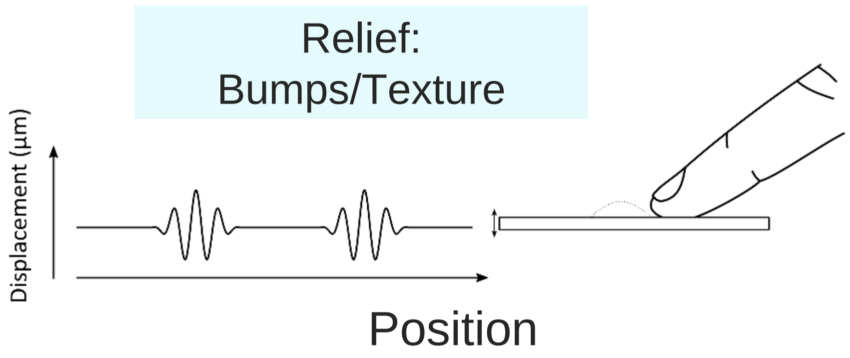


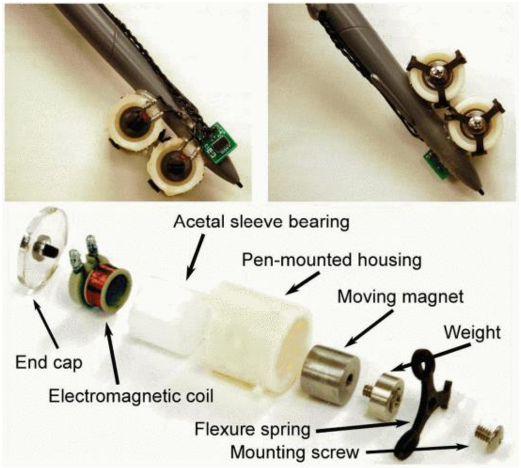
Vallbo, A. B., & Johansson, R. S. Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Human neurobiology*, 1984

Shao et al., Spatial patterns of cutaneous vibration during whole-hand haptic interactions, *PNAS,* 2016

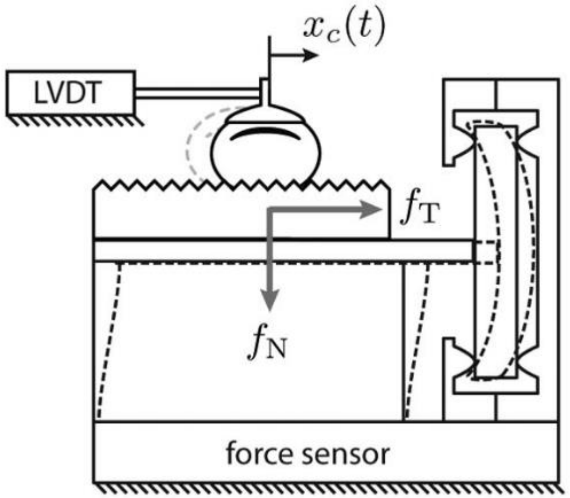
Stimulation vibrotactile

Restitution de textures





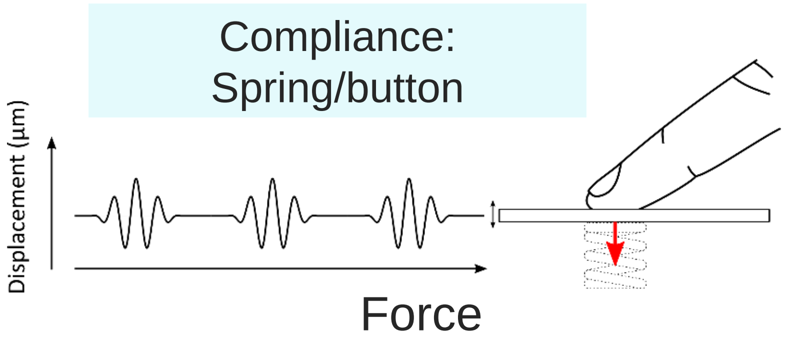
J. M. Romano and K. J. Kuchenbecker, "Creating Realistic Virtual Textures from Contact Acceleration Data" in *IEEE Transactions on Haptics*, 2012

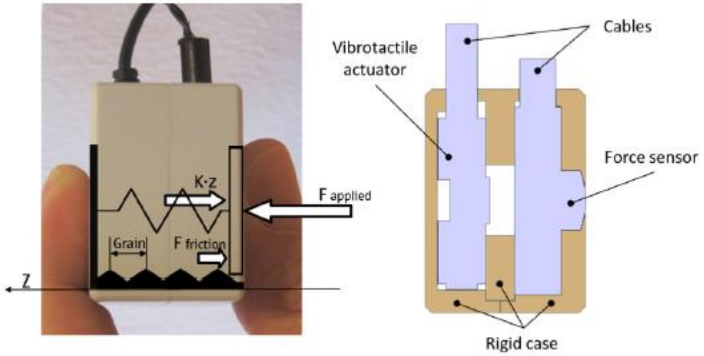


Wiertlewski et al. "The Spatial Spectrum of Tangential Skin Displacement Can Encode Tactual Texture," in *IEEE Trans. on Robotics*, 2011

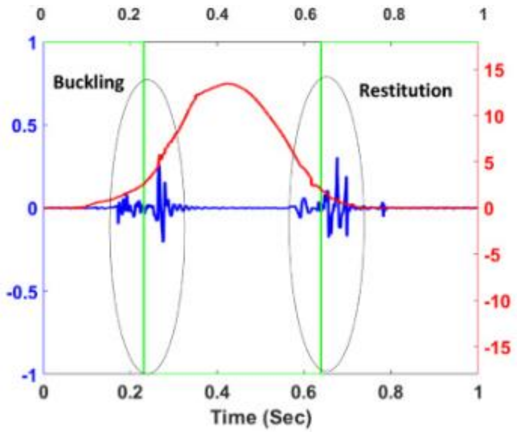
Stimulation vibrotactile

Restitution de raideur

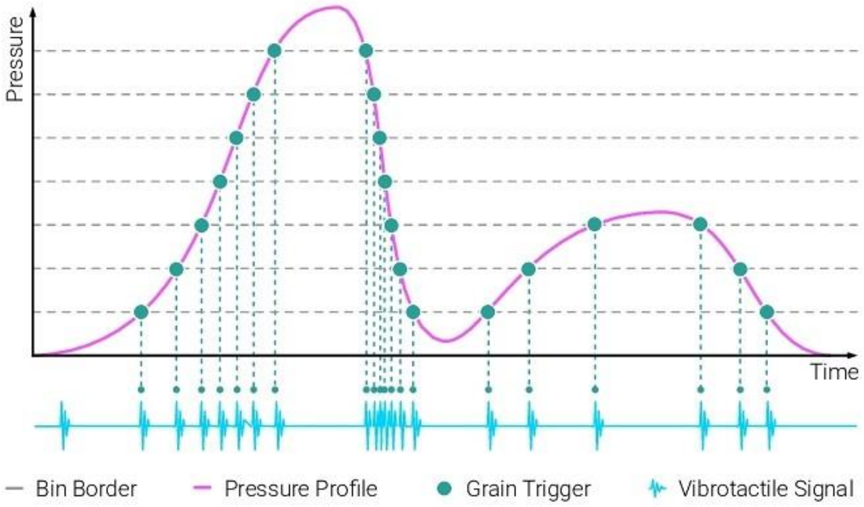




Kildal, Kooboh: Variable Tangible Properties in a Handheld Haptic-Illusion Box, Eurohaptics 2012



Sadia et al., Data-driven vibrotactile rendering of digital buttons on touchscreens, Int. J. of Human-Computer Studies, 2020



Vega et al., VARitouch: Back of the Finger Device for Adding Variable Compliance to Rigid Objects. In Proc. CHI 2024

Actionnement piézoélectrique

Principe

σ Tenseur des contraintes (Pa)

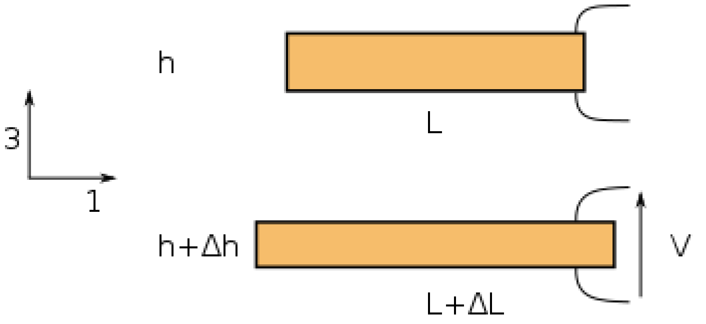
ε Tenseur des déformations (m/m)

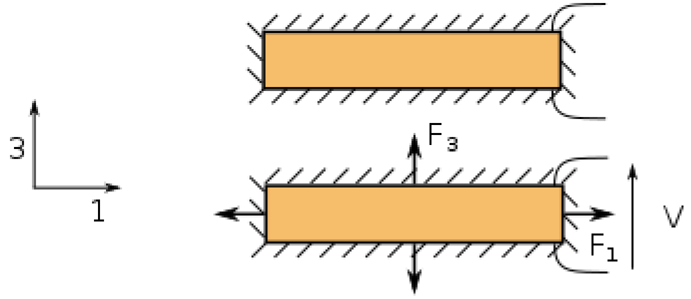
E Vecteur champ électrique ($V.m^{-1}$)

Matériau élastique linéaire	Matériau piézoélectrique
$\varepsilon = s\,\sigma$	$\varepsilon = s^E\,\sigma + d'E$
$\sigma = c\,\varepsilon$	$\sigma = c^E\,\varepsilon - e'E$
s Matrice de souplesse (Pa^{-1})	s^E Matrice de souplesse à E=0 (Pa^{-1})
c Matrice de raideur (Pa)	c^E Matrice de raideur à E=0 (Pa)
	d Matrice d'effet piézoélectrique directe (m/V)

Actionnement piezoélectrique

Applications numériques





$$\Delta \boldsymbol{L} = \varepsilon_1^{\sigma=0} L = d_{31} E_3 L = -d_{31} \frac{V}{h} L = \mathbf{-170\ nm}$$

$$\boldsymbol{F_1} = \sigma_1^{\varepsilon=0} S_{side} = -e_{31} E_3 S_{side} = e_{31} \frac{V}{h} S_{side} = \mathbf{-1,5\ N}$$

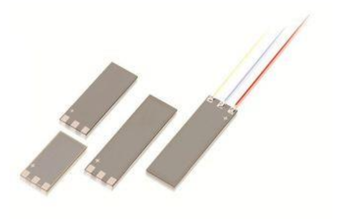
$$\Delta \boldsymbol{h} = \varepsilon_3^{\sigma=0} h = d_{33} E_3 h = -d_{33} V = \mathbf{22.5\ nm}$$

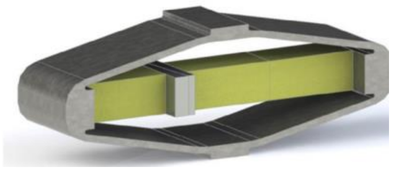
$$\boldsymbol{F_3} = \sigma_3^{\varepsilon=0} S_{top} = -e_{33} E_3 S_{top} = e_{33} \frac{V}{h} S_{top} = \mathbf{160}\ \boldsymbol{N}$$

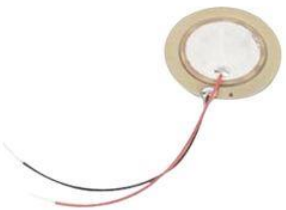
Céramique Ferroperm PZ27:
$d_{31} = -1.7\ 10^{-10}$ C/N, $d_{33} = 4.5\ 10^{-10}$ C/N, $e_{31} = -3{,}09$ C/m², $e_{33} = 16$ C/m²
$h = 500$ µm, $L = 10$ mm, $V = 10$ V

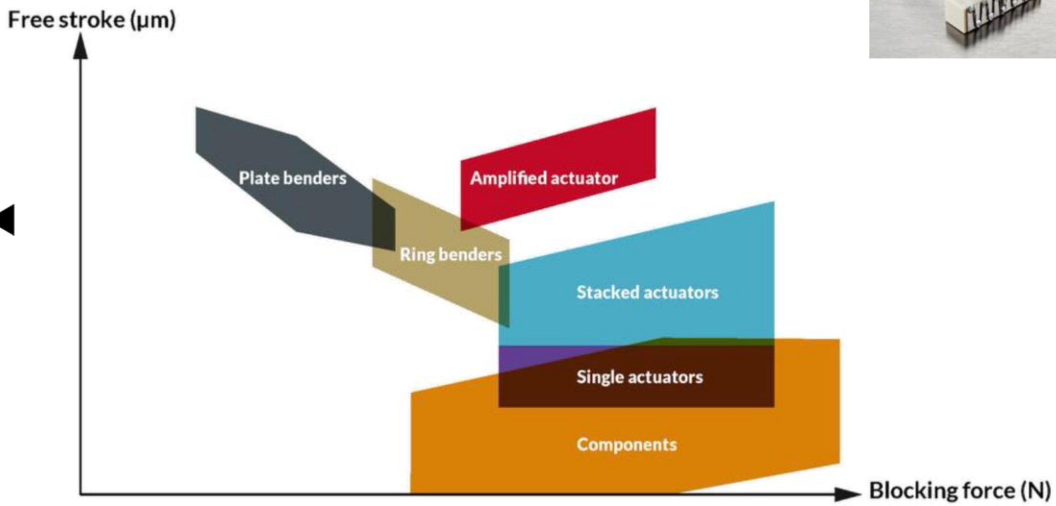
Actionnement piezoélectrique

Typologie d’actionneurs

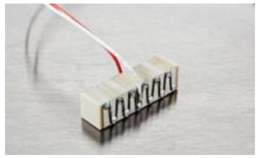


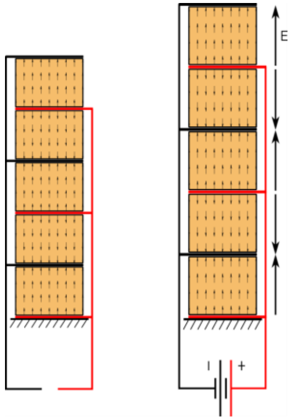


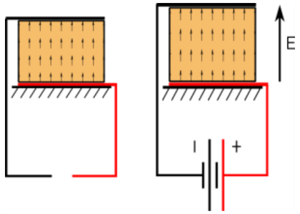




Source: Noliac piezo tutorial

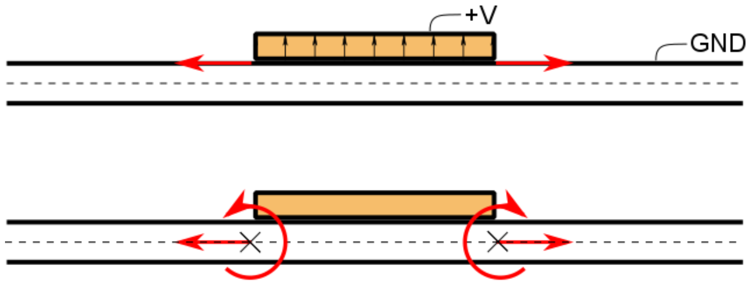


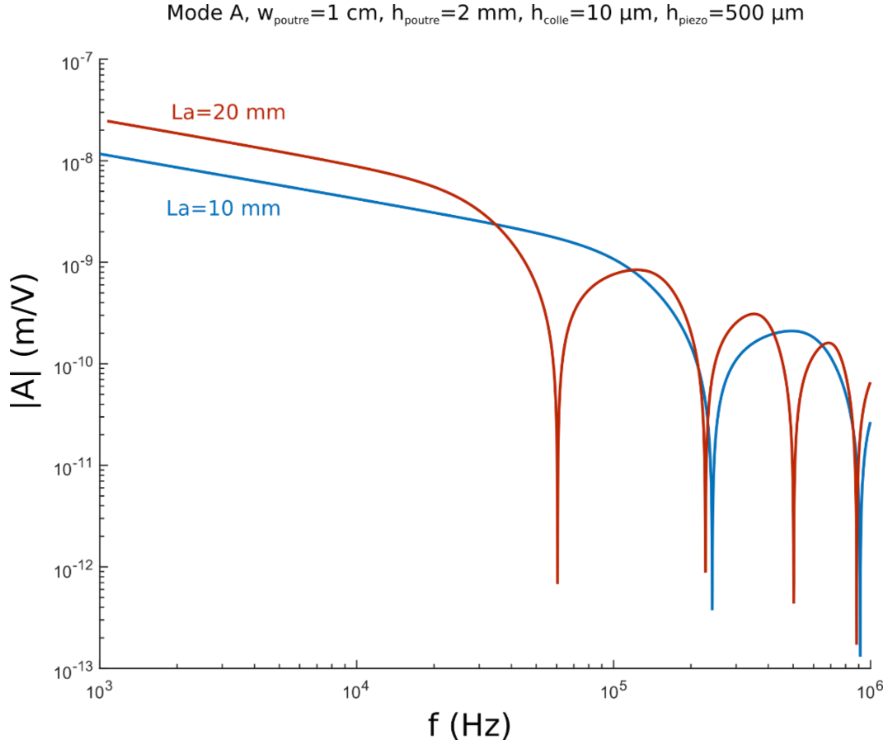




Actionnement piezoélectrique

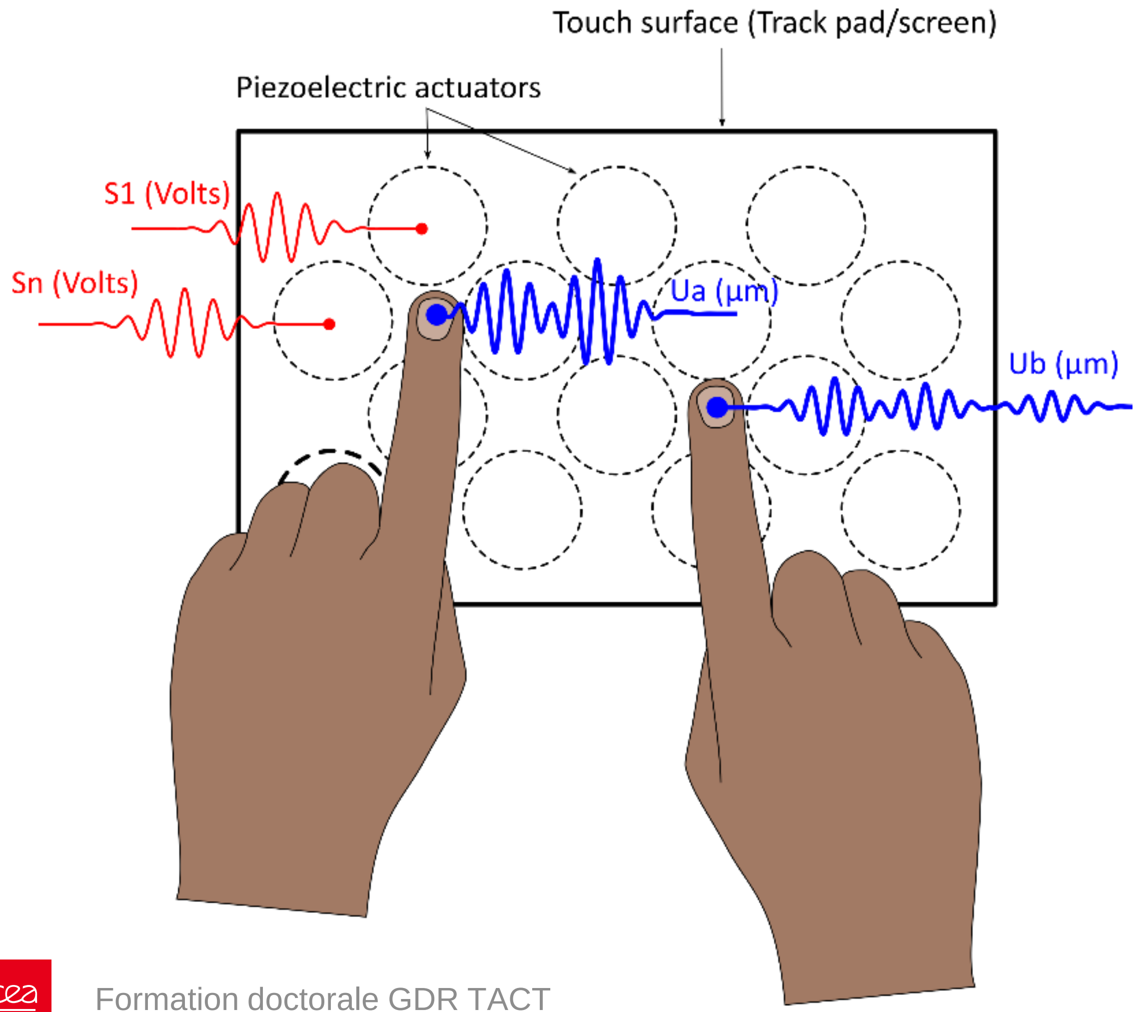
Benders





Stimulation vibrotactile localisée

Principe du filtrage inverse 1



Surface displacement = Propagation matrix . Driving signals

$$\begin{bmatrix} U_a \\ U_b \end{bmatrix} = \begin{bmatrix} H_{1a} & \dots & H_{Na} \\ H_{1b} & \dots & H_{Nb} \end{bmatrix} \begin{bmatrix} S_1 \\ \dots \\ S_N \end{bmatrix}$$

- Propagation
- Reverberation
- Dispersion

Stimulation vibrotactile localisée

Principe du filtrage inverse 2

Surface displacement — Propagation matrix — Driving signals

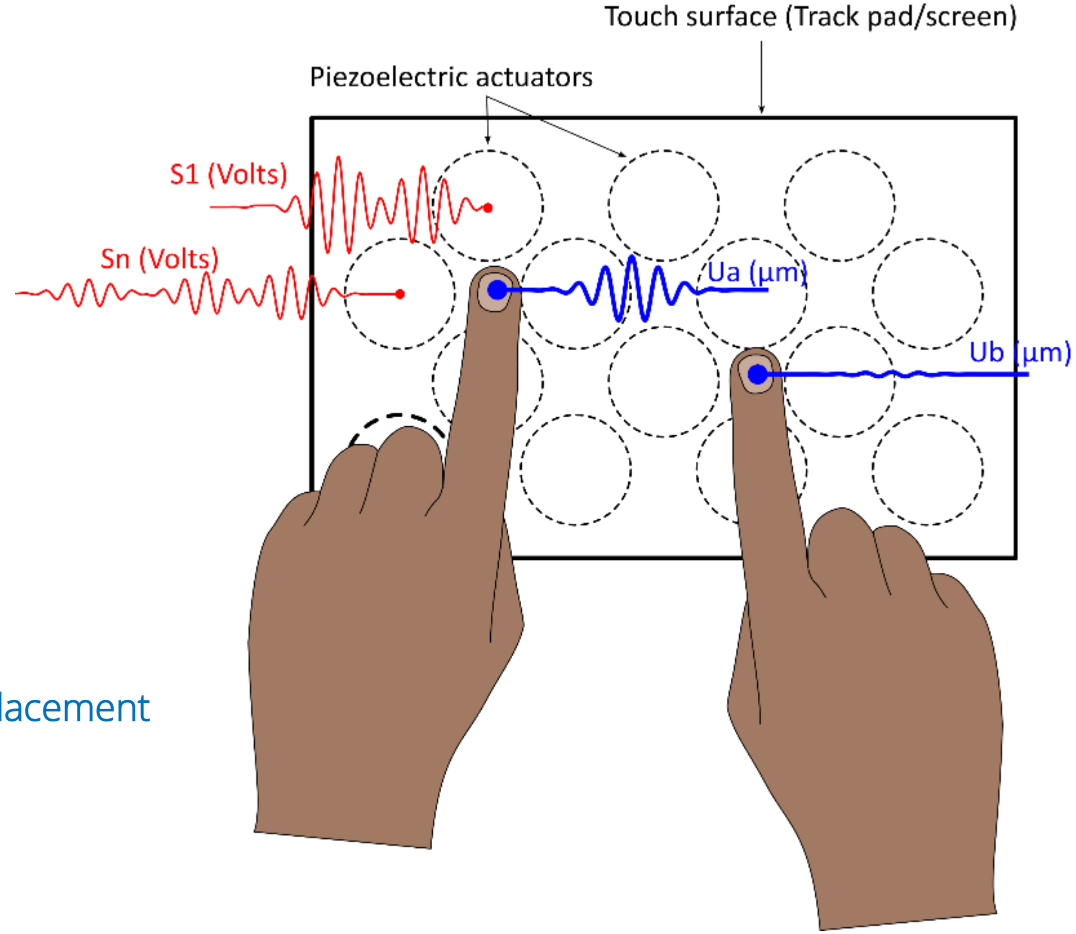
$$\begin{bmatrix} U_a \\ U_b \end{bmatrix} = \begin{bmatrix} H_{1a} & \dots & H_{Na} \\ H_{1b} & \dots & H_{Nb} \end{bmatrix} \begin{bmatrix} S_1 \\ \dots \\ S_N \end{bmatrix}$$

$$\begin{bmatrix} U_a \\ U_b \end{bmatrix} = \begin{bmatrix} H_{1a} & \dots & H_{Na} \\ H_{1b} & \dots & H_{Nb} \end{bmatrix} \begin{bmatrix} H_{1a} & \dots & H_{Na} \\ H_{1b} & \dots & H_{Nb} \end{bmatrix}^{-1} \begin{bmatrix} \widetilde{U}_a \\ \widetilde{U}_b \end{bmatrix}$$

Inverse matrix

Desired displacement

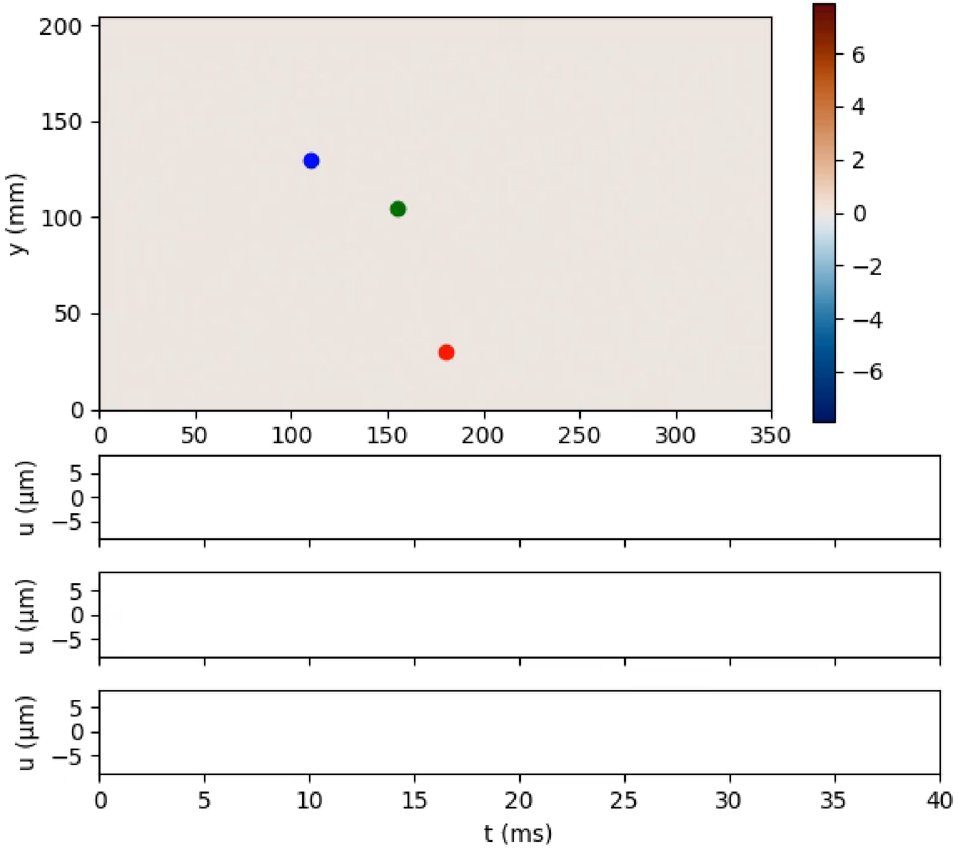
$$\begin{bmatrix} U_a \\ U_b \end{bmatrix} = \begin{bmatrix} \widetilde{U}_a \\ \widetilde{U}_b \end{bmatrix}$$



Stimulation vibrotactile localisée

Mise en œuvre du filtrage inverse

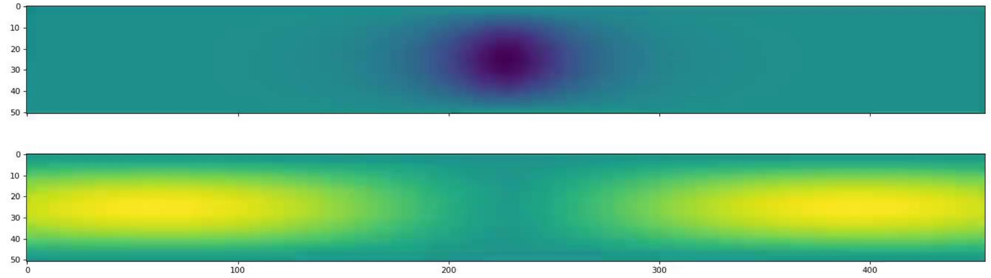
Ecran OLED equipé d’actionneurs piezoélectriques, CEA 2024



Localized haptics with inverse filtering - CEA - 2023

Stimulation vibrotactile localisée

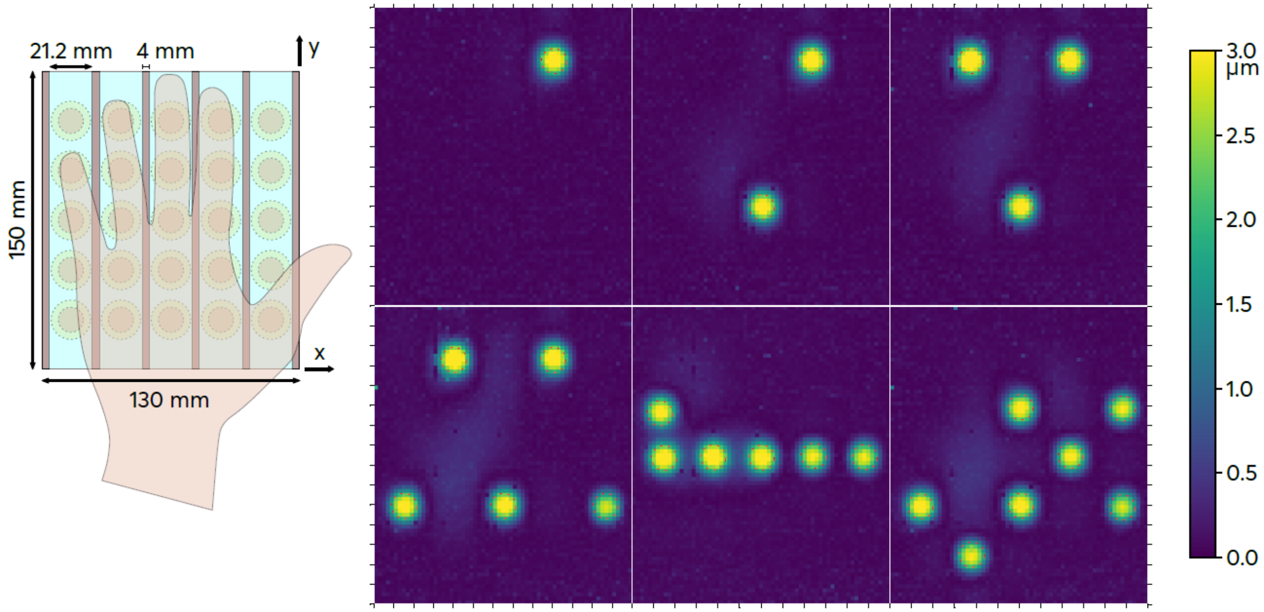
Localisation par guide d'onde



Une plaque étroite maintenue sur ses bords longs forme un guide d'onde.

En dessous d'une fréquence de coupure, les ondes ne se propagent pas et restent confinées au dessus des actionneurs.

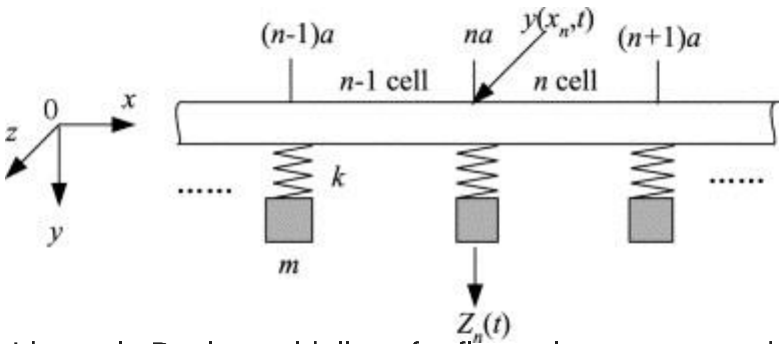
On peut ainsi s'affranchir de la propagation des ondes et créer des pixels vibrotactiles sur une surface.



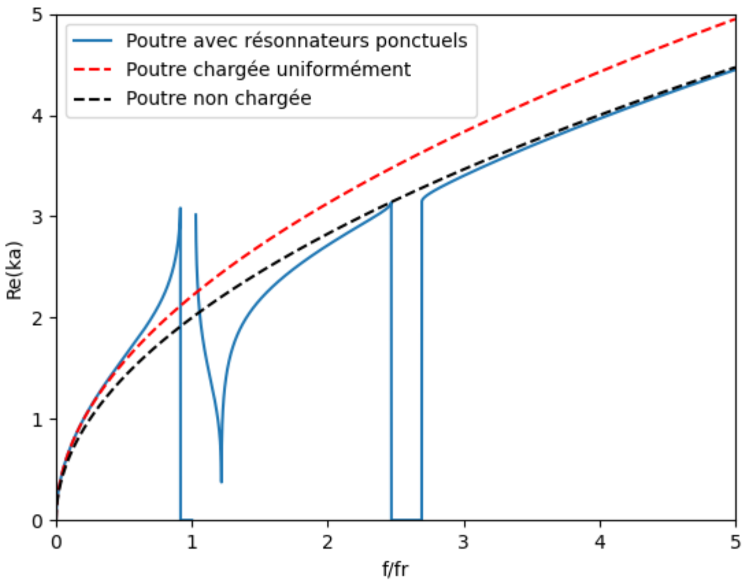
A. Ben Dhiab and C. Hudin, 'Confinement of Vibrotactile Stimuli in Narrow Plates. - Principle and Effect of Finger Loading -', *IEEE Transactions on Haptics, 2020*

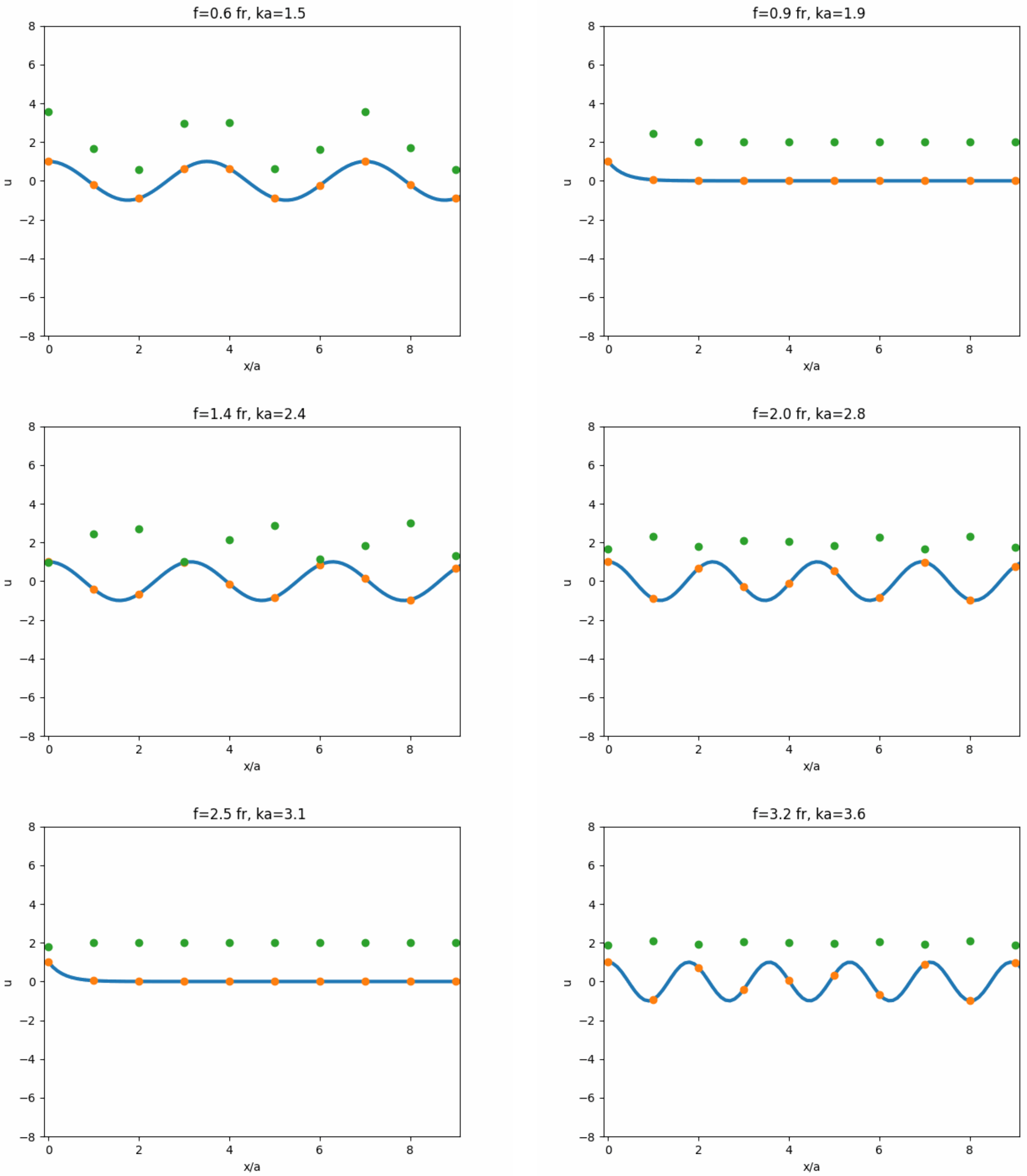
Métamatériaux

Principe



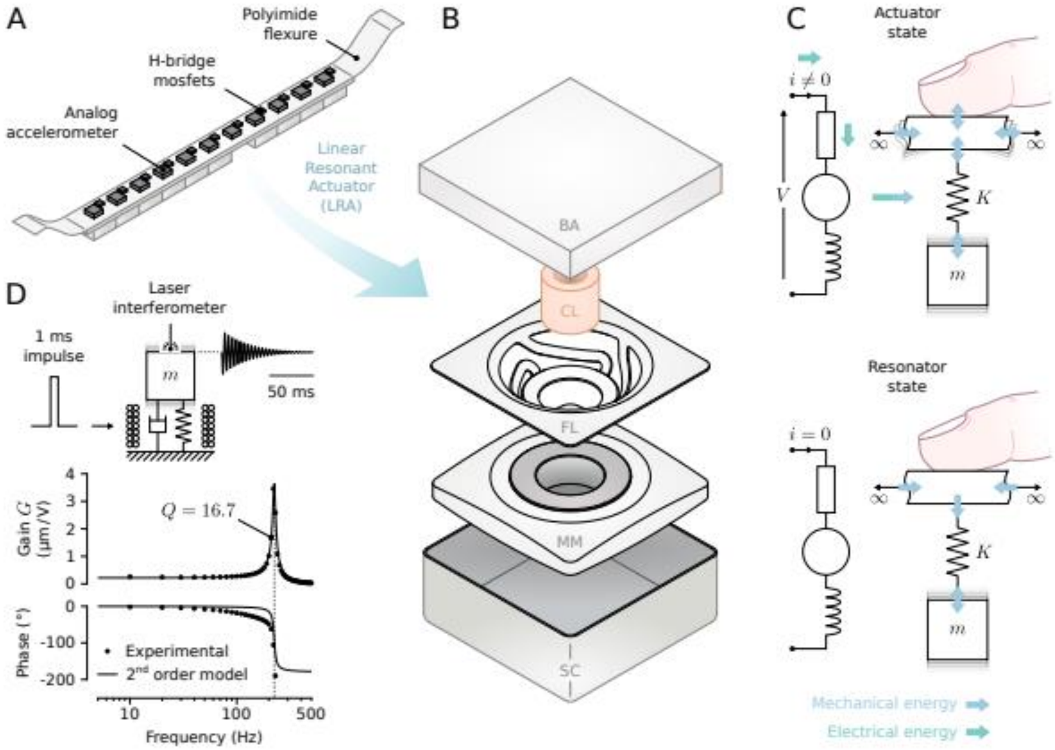
Liu et al., Design guidelines for flexural wave attenuation of slender beams with local resonators. *Physics Letters A*, 2007.

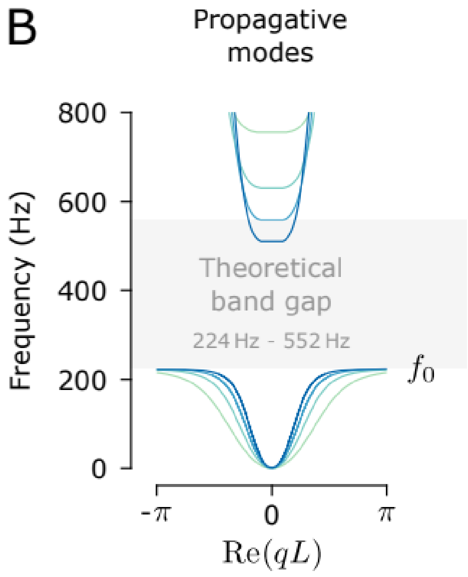




Métamatériaux

Localisation dans la bande vibrotactile

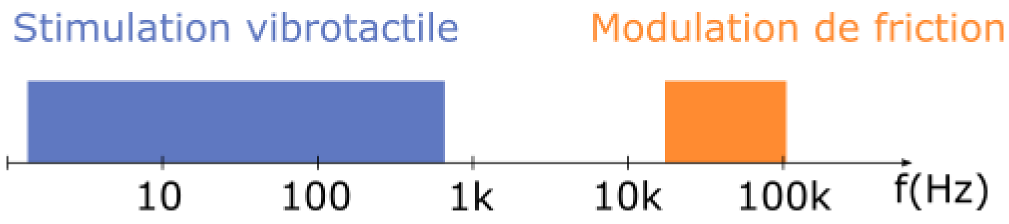


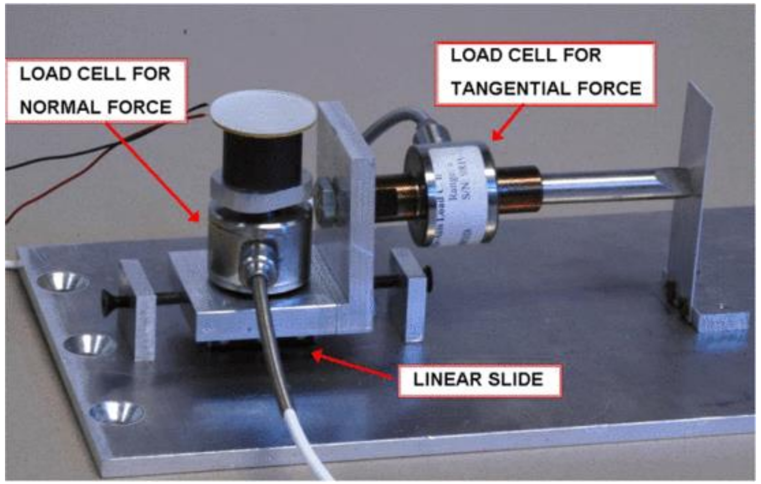


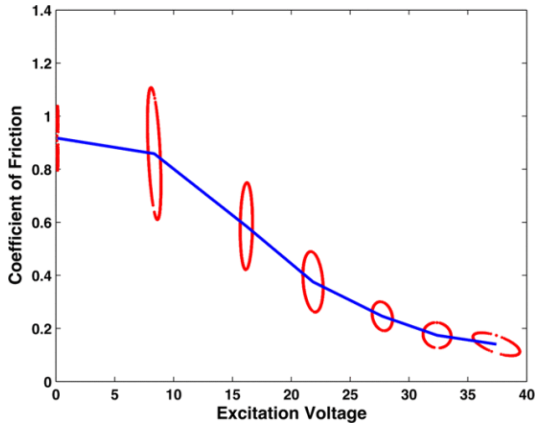
Daunizeau et al., Dynamic Shaping of Multi-Touch Stimuli by Programmable Acoustic Metamaterial, 2024

Modulation de friction ultrasonore

Principe







Winfield et al., "T-PaD: Tactile Pattern Display through Variable Friction Reduction," *In proc. IEEE WHC 2007*

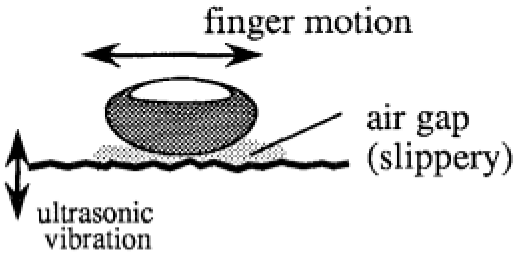


Figure 4: A feeling of 'air smoothness'.

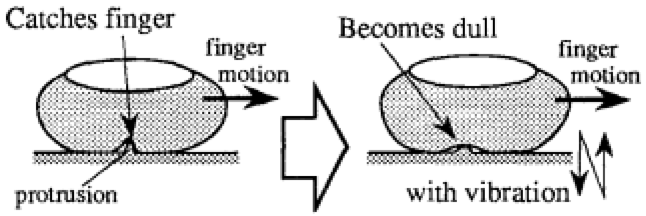
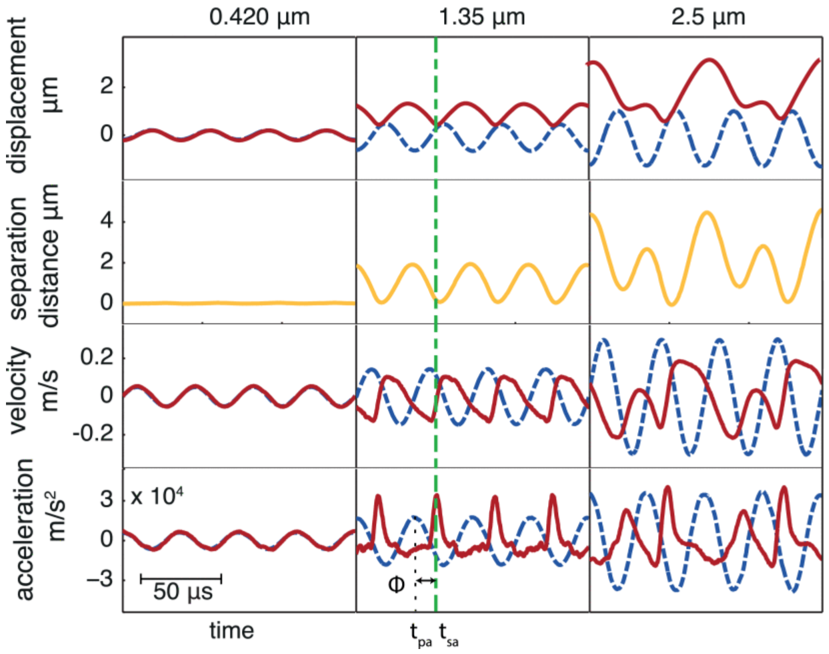


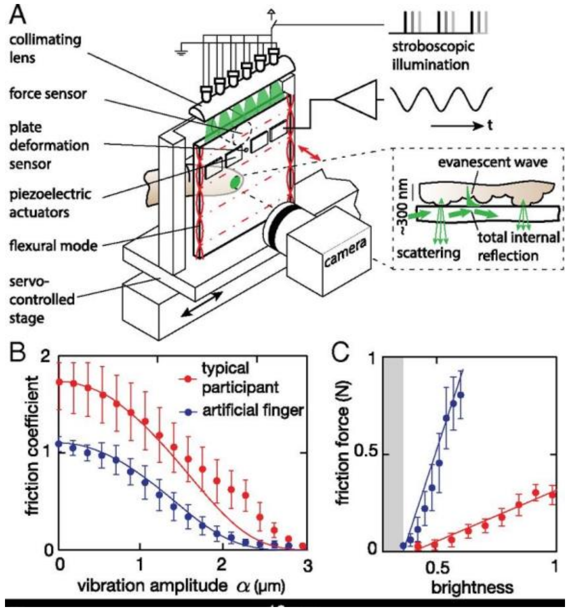
Figure 5: Perceived surface configuration.

Watanabe et al. "A method for controlling tactile sensation of surface roughness using ultrasonic vibration," *Proc. ICRA 1995*

Modulation de friction

Principe



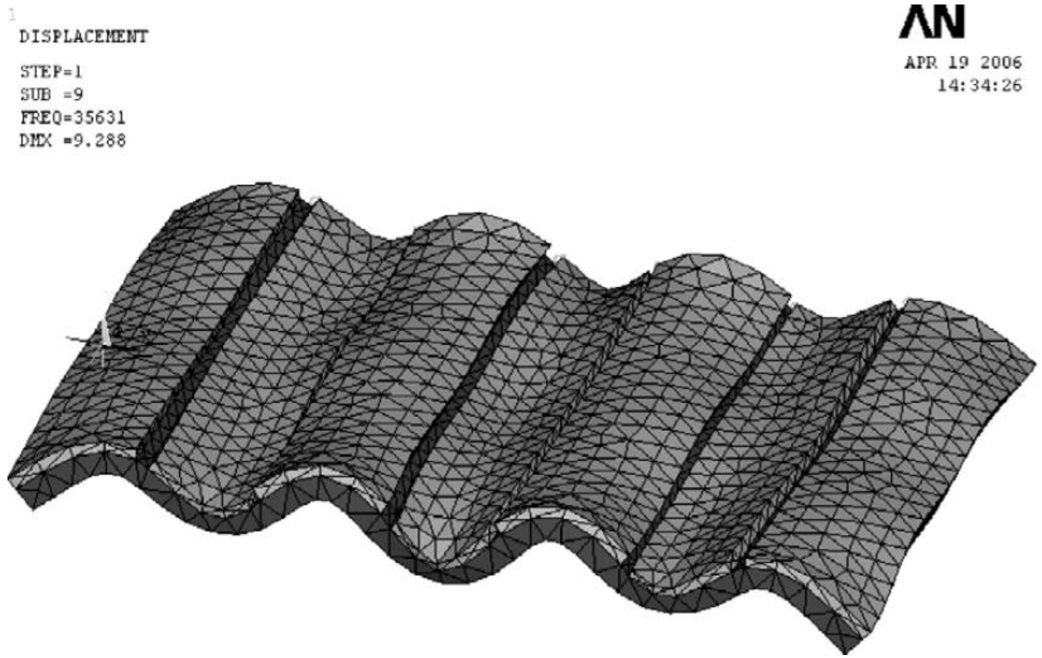


E. Vezzoli *et al*., "Friction Reduction through Ultrasonic Vibration Part 1: Modelling Intermittent Contact," in *IEEE Trans. on Haptics*, 2017

M. Wiertlewski et al., Partial squeeze film levitation modulates fingertip friction, *PNAS 2016*

Modulation de friction ultrasonore

Mise en oeuvre



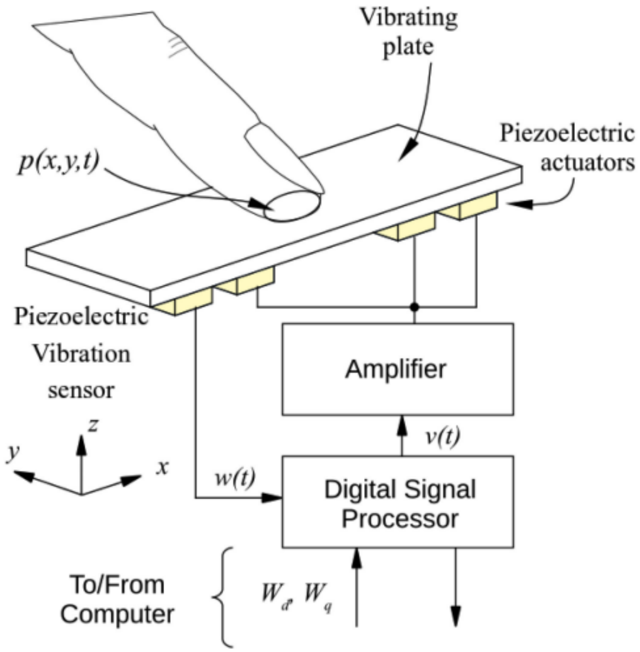
Biet et al., "Squeeze film effect for the design of an ultrasonic tactile plate," in IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control, 2007

Giraud et al., "Design of a transparent tactile stimulator," *IEEE Haptics Symposium, 2012*.

Modulation de friction ultrasonore

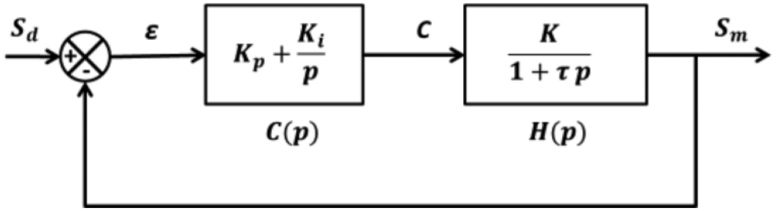
Mise en œuvre en boucle fermée

Contrôle de la force de friction



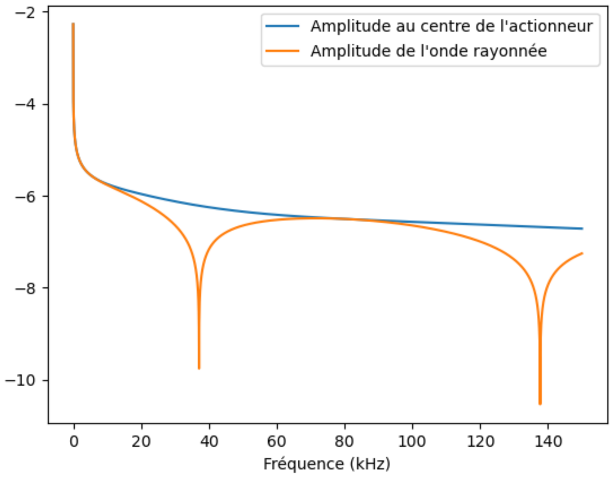
Kaci et al., "Fundamental Acoustical Finger Force Calculation for Out-of-Plane Ultrasonic Vibration and its Correlation with Friction Reduction," *IEEE World Haptics Conference (WHC)*, Tokyo, Japan, 2019

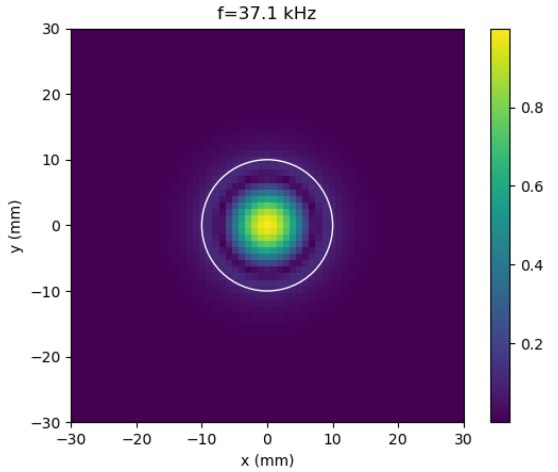
Contrôle de l'amplitude de vibration

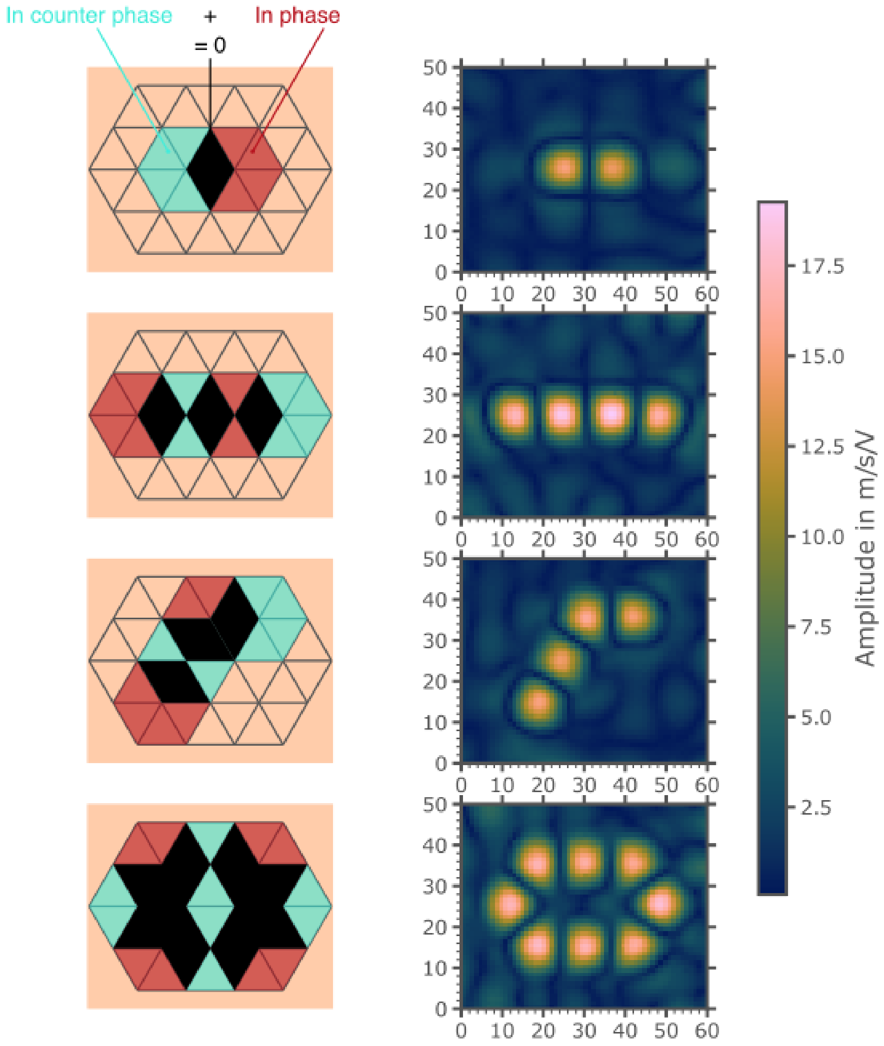


Ben Messaoud et al., "Amplitude Control of an Ultrasonic Vibration for a Tactile Stimulator," in *IEEE/ASME Trans. on Mechatronics* 2016

Confinement des ondes par fréquences non rayonnantes.







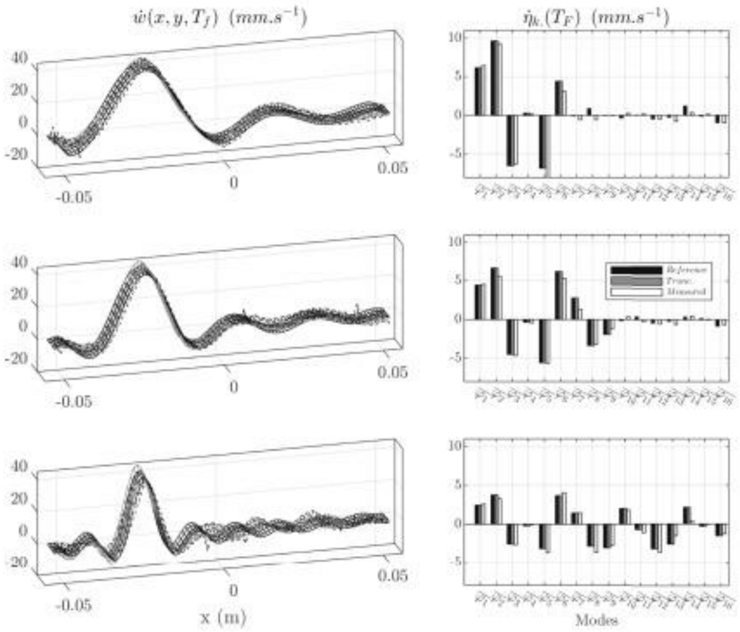
Thèse A. Ben Dhiab. Confinement of Vibrations for Localized Surface Haptics. Sorbonne Université, 2022

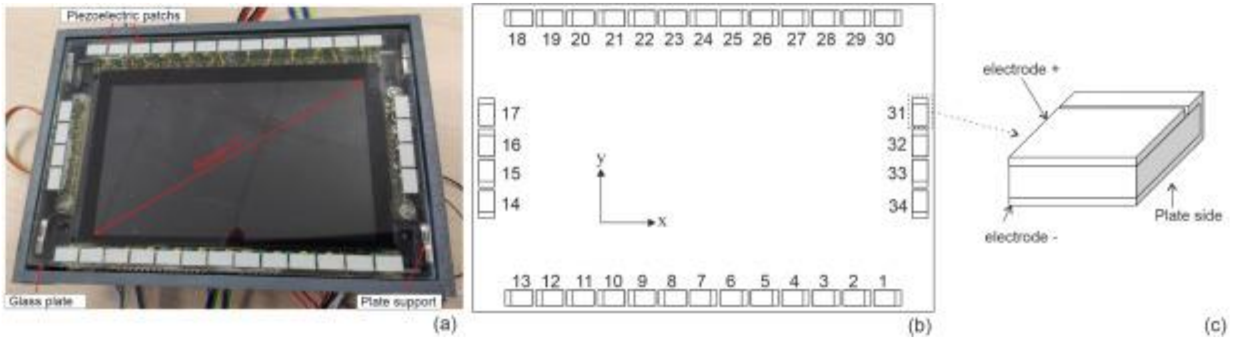
A certaines fréquences ultrasonores, un actionneur piezoélectrique circulaire ne rayonne pas d’ondes de flexion.

On peut approximer un disque par une combinaison hexagonale d’électrodes triangulaires.

On crée ainsi des pixels capables de moduler localement la friction d’un doigt à la surface de l’écran

Localisation par superposition modale





Kaci et al., Closed loop control of vibration field transient: Application to wave focusing. *Mechanical Systems and Signal Processing*. 2022

Enferad et al., Generating controlled localized stimulations on haptic displays by modal superimposition. *J. of Sound and Vibration*. 2019

Confinement par métamatériaux

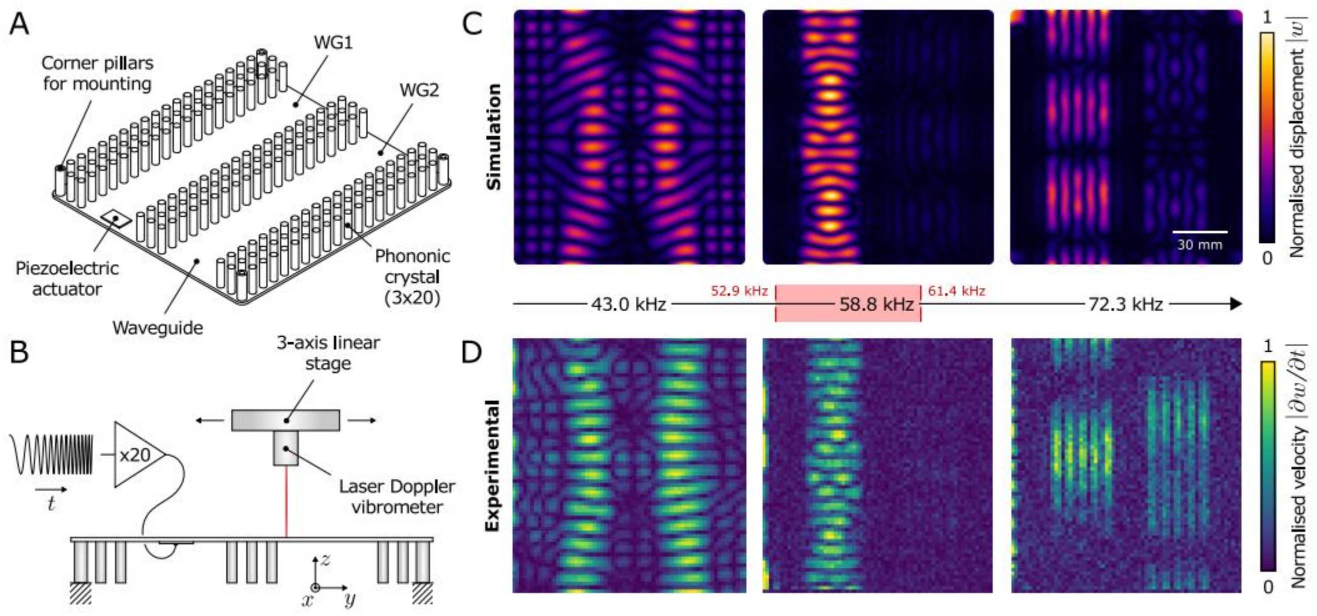


Fig. 5. (A) Schematic of the ultrasonic plate with two independent waveguides WG1 and WG2 (bottom view). (B) Experimental setup with the laser Doppler vibrometer scanning the plate fixed on its four corners (side view). (C) From left to right, numerical simulations of the modal response for three given frequencies respectively, below, inside, and above the band gap (top view). Only transverse displacements w along the z-axis are shown. (D) Optical vibrometry measurements of the modal response for the same frequencies (top view). Velocities along the z-axis are normalised to emphasize mode shapes.

Daunizeau et al., Phononic crystals applied to localised surface haptics. *IEEE Trans.on Haptics*, *2021*

Confinement par rupture d'impédance

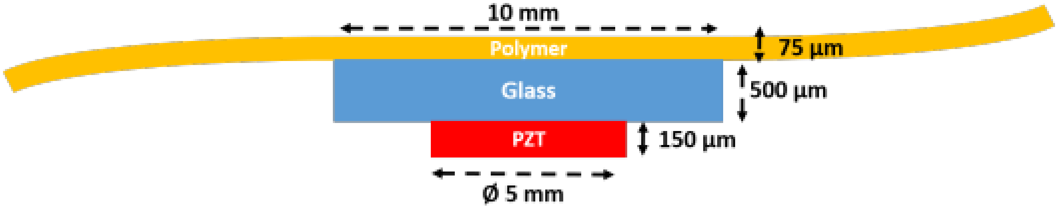
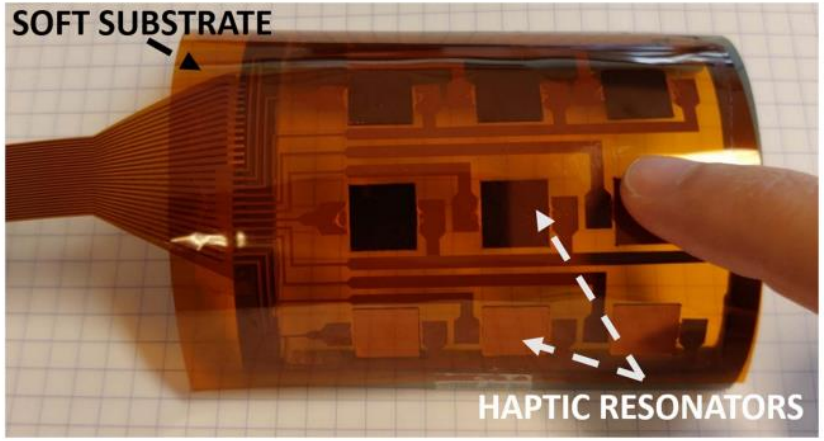


Fig. 1. Haptic pixel concept



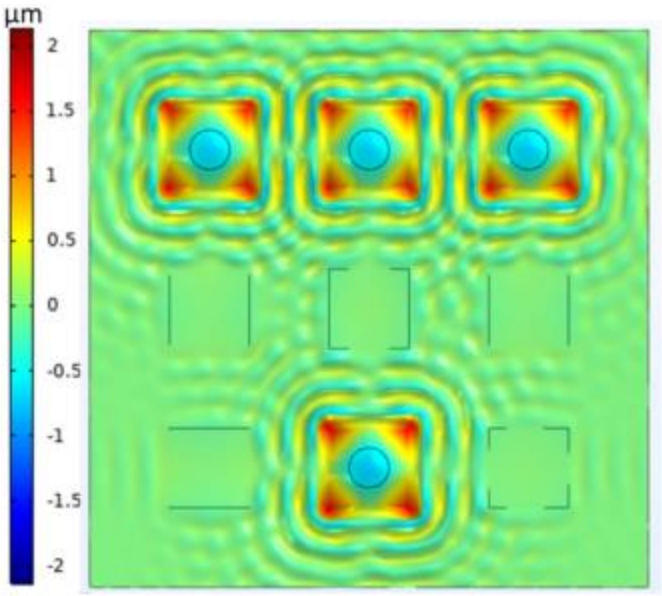
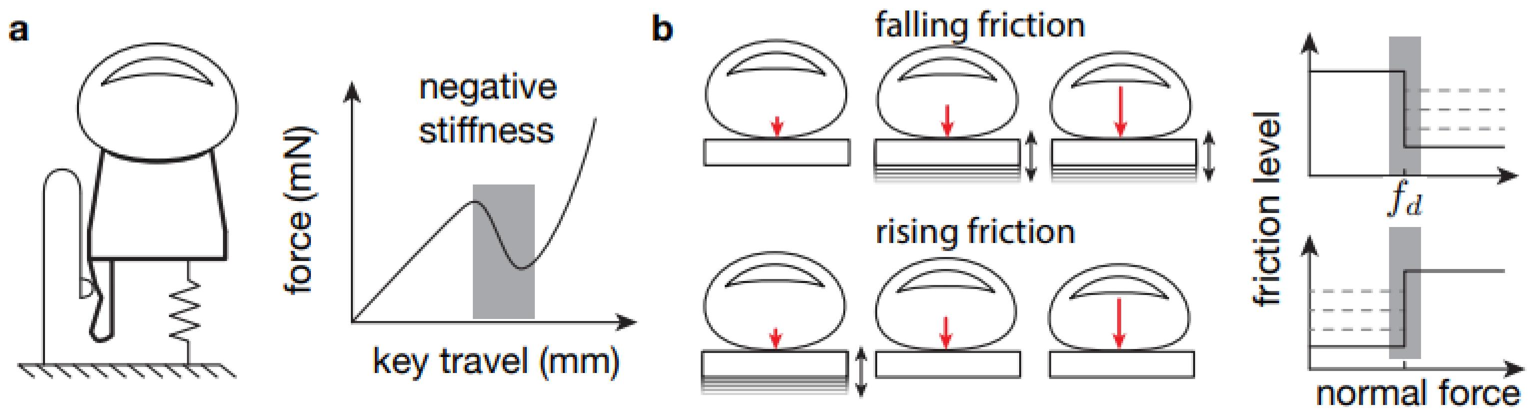


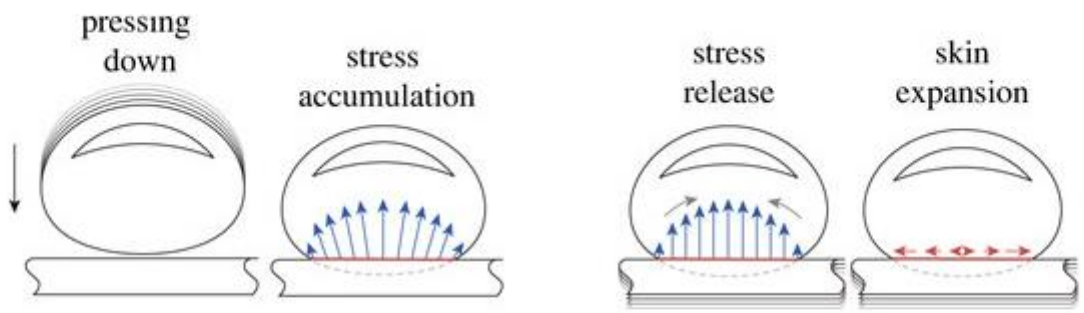
Fig. 4. Displacement field to obtain a line and a point on COMSOL.

R. Le Magueresse *et al.*, "Reconfigurable Flexible Haptic Interface Using Localized Friction Modulation," in *IEEE Trans. on Haptics,* 2025

Button click rendering



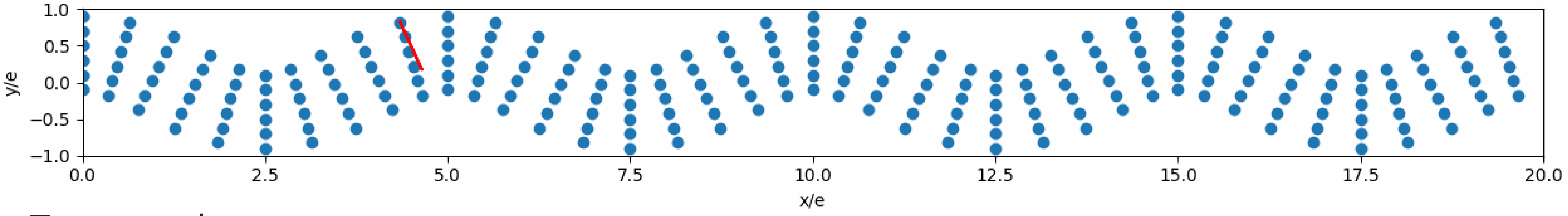
Monnoyer et al., Ultrasonic friction modulation while pressing induces a tactile feedback. *EuroHaptics 2016*.



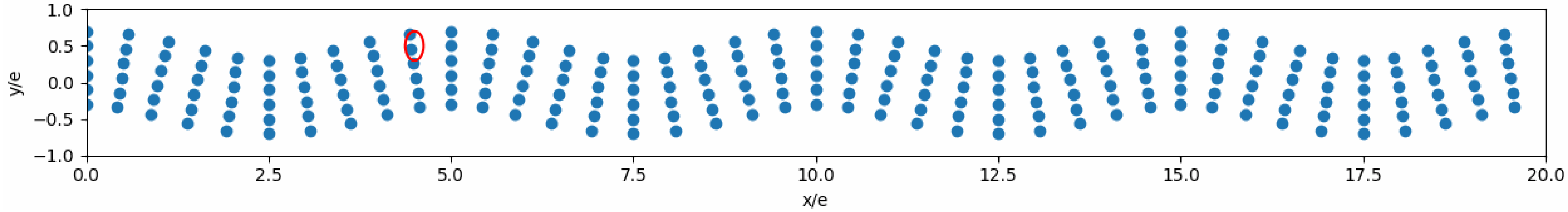
Monnoyer et al., Rapid change of friction causes the illusion of touching a receding surface, *J. R. Soc. Interface.* 2023

Force latérale nette: mouvement elliptique

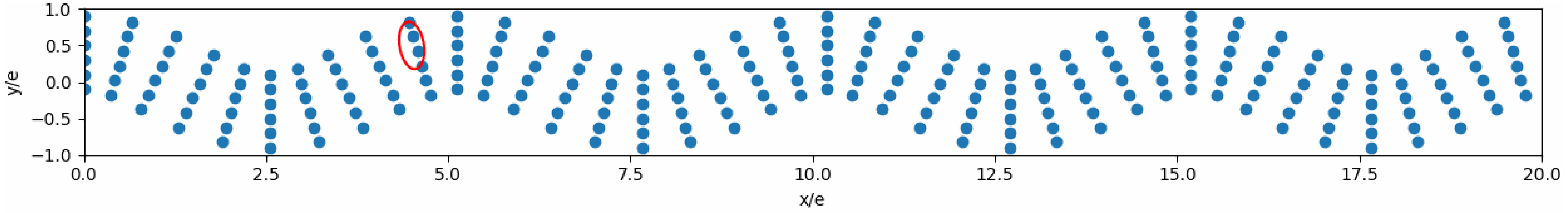
Onde T stationnaire



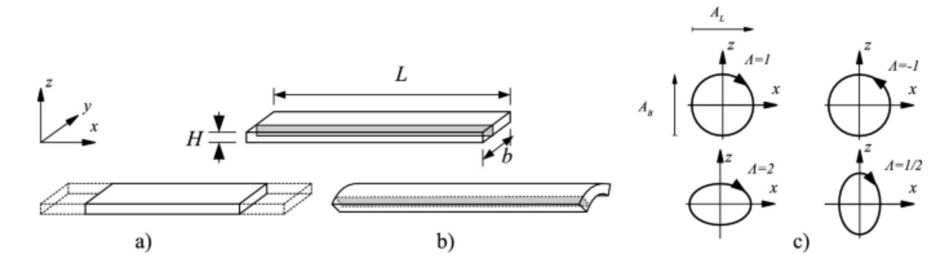
Onde T progressive



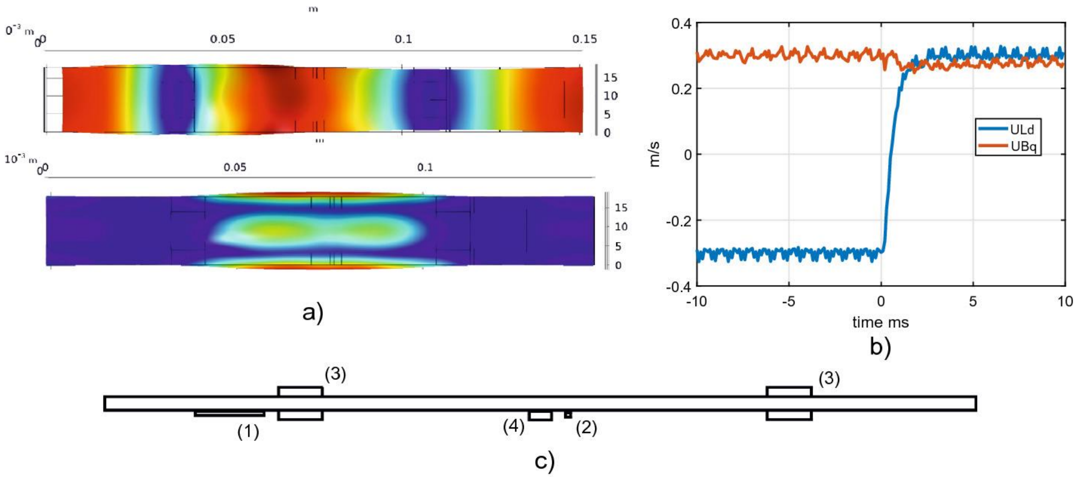
Onde T stationnaire + onde L déphasée



Modes T et L concordants

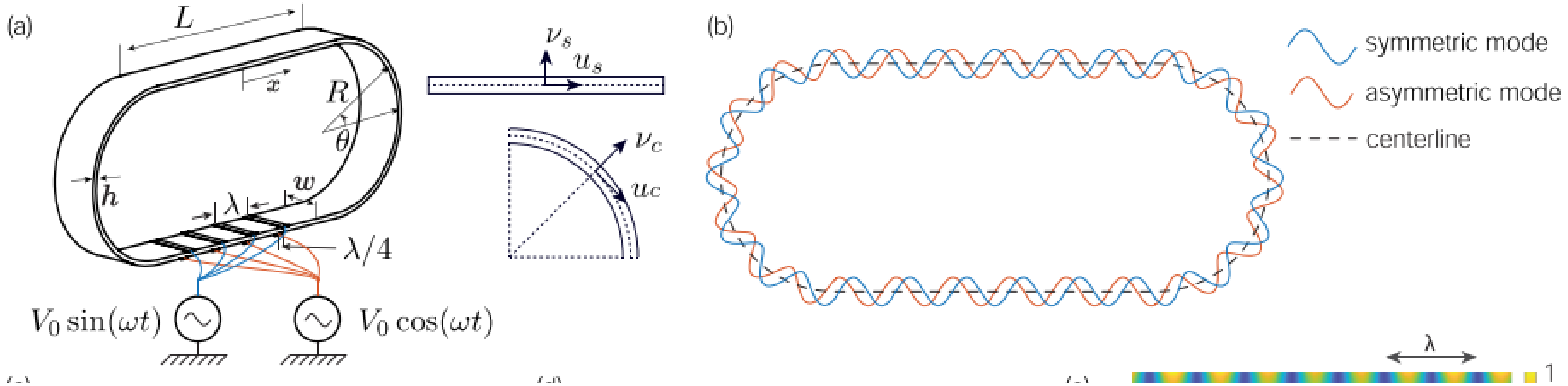


Vibration mode a) Longitudinal, b) bending and c) Elliptical motion in the middle of the top surface for several values of Λ



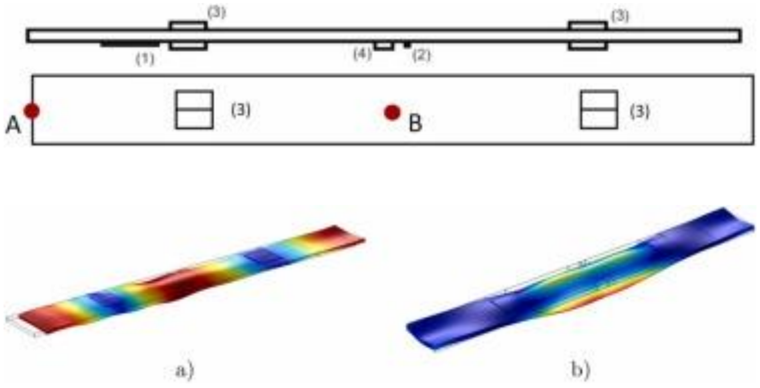
Garcia et al., 2MoTac: Simulation of Button Click by Superposition of Two Ultrasonic Plate Waves. In proc. EuroHaptics 2020

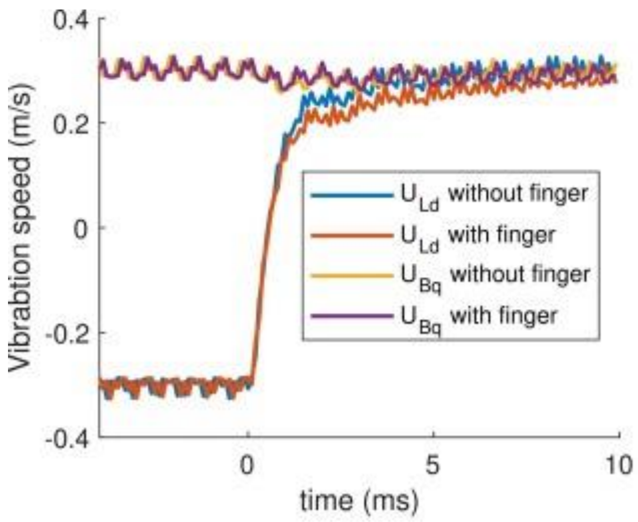
Modes T dégénérés



Cai et al., Ultraloop: Active lateral force feedback using resonant traveling waves, 2023

Modes T et L concordants en boucle fermée





Pierre Garcia, Control of an ultrasonic haptic interface for button simulation,Sensors and Actuators A: Physical,
2022,

Conclusion et Perspectives

On peut, en contrôlant les vibrations de la surface:

- Reproduire la texture macroscopique (cm) d'une surface en créant par un mouvement elliptique une force latérale à l'échelle du doigt.
- Reproduire la texture microscopique (100 µm) d'une surface en reproduisant les vibrations induites par le glissement.

Un défi reste de reproduire une texture mésoscopique, à l'échelle du mm, qui se traduit par des variations du champ de contrainte à l'intérieur de la zone de contact doigt/surface.

Une autre défi est de produire une force nette homogène sur une surface plane 2D et dans les deux directions du plan.