Confinement of Vibrotactile Stimuli in Periodically Supported Plates

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Abstract. For multitouch and multiuser interactions on a touch surface, providing a local vibrotactile feedback is essential. Usually, vibration propagation impedes this localization. Previous work showed that narrow strip-shaped plates could allow the confinement of vibrotactile stimuli to the actuated area. Adding to this principle, periodically supported plates also provide a non-propagative effect at low frequencies. Using both geometrical properties, we provide a device allowing a multitouch interaction through an array of piezoelectric actuator. Experimental validation show that vibrations are well confined on top of actuated areas with vibration amplitude over 2 µm.

Keywords: Surface haptics · Confinement · Vibrotactile stimuli · Narrow plate · Ribbed plate · Non-propagating · Evanescent wave · Vibrations

1 Introduction

Wave propagation in today's surface haptic interfaces limits the user to a single point of interaction whereas most exploratory procedures benefit from the use of multiple fingers to properly process surface information [7]. Solving this problem requires to localize vibrations. There are several methods related to technologies that allow localized haptic feedback on continuous surfaces. For spatial localization of vibrations, i.e., the creation of local deformation at a point or area of the plate, there are two techniques: *Time-Reversal* [5] and *Modal Superimposition* [4]. For these two techniques, the wavelength of the vibrations to obtain a local deformation at the centimeter or millimeter scale necessarily involves high frequencies. The *Time-Reversal Wave Focusing* technique uses the propagation of elastic waves to generate constructive interference at a given time and position on the plate. The acceleration peak created by the focusing of the waves causes the ejection of a static or moving fingerpulp, giving a haptic feedback smaller than the fingertip. However, this approach needs a calibration procedure and is subjected to external parameters (e.g. temperature, finger interaction), which can impede the tactile stimulation. As for *Modal Superimposition*, it uses a truncated modal decomposition to focus a deformation shape and control its position. The high frequencies produced by an array of piezoelectric actuators

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allow for the appearance of a tactile lubrication phenomenon, i.e. a variation in friction that is only felt when the finger is moved [10]. Both techniques rely on propagation of high frequency waves. During user interaction, the non-linear behavior of the finger significantly modifies the vibrational behavior of the plate. Such modifications are particularly striking for high frequencies thus leading to many complications (incl. flexural waves scattering, mode damping, mode translation). In order to avoid these limitations and provide a haptic feedback both to static and moving fingers, the *Inverse-Filter* approach [8] proposes to dynamically control low-frequency waves, which are less impacted by finger interaction, to provide the user with the desired stimuli only at the contact points. Nonetheless, this technique is based on (consequent) computation, signal processing and calibration procedures. As this technique uses waves within the tactile frequency range (0–1 kHz), it induces a global movement of the plate and therefore limits the interaction to five control points. Generally, all the previously mentioned methods depend on wave propagation and thus, are in need of calculations and signal processing in order to achieve localization. Therefore, we have investigated in our previous work [1] another method that overcomes such requirements by relying on geometry features and wave evanescence instead. We have shown that it is possible to obtain localized deformations above the actuators for low frequency signals in narrow thin plates (1D). A particularity of this technique is that it allows the spatial localization of low-frequency stimuli i.e. a local deformation of the plate even if we use low-frequencies with long wavelength. In addition, finger interaction does not attenuate low-frequency evanescent waves. No matter the surface in contact, i.e. finger, hand, arm, foot... the behavior of the vibrating plate is not impacted and a localized stimuli can be provided. Although interesting, this approach is limited to narrow plates. However, for a rich multitouch interaction, extending this approach to an arbitrary 2D plate becomes necessary and is the focus of this paper. Because waves tend to directly propagate in 2D plates, the confinement i.e. the suppression of propagative waves in favor of evanescence, was not easily achieved. In order to do so, we used a theoretical result raised by Mead [6]. He states that a periodically supported beam exhibits a non-propagating low-frequency band up to the first resonant mode of isolated segments. Meaning in our case that if we have a periodically bounded plate and if each formed areas have each a waveguide geometry, a cut-off frequency exists and we can have the spatial localization of low frequency stimuli. Therefore, in this paper, we verify this assumption experimentally with a novel setup and discuss the various possibilities it opens up.

2 Principle

2.1 Confinement by the Ribs

In this section we explain how vibrations can be confined along both axis of a ribbed plate depicted in Fig. 1. On the x-axis, we find ourselves solving a problem of an infinite beam supported periodically (Fig. 1). Regularly supported beams can be seen as a set of individual supported beam portions applying

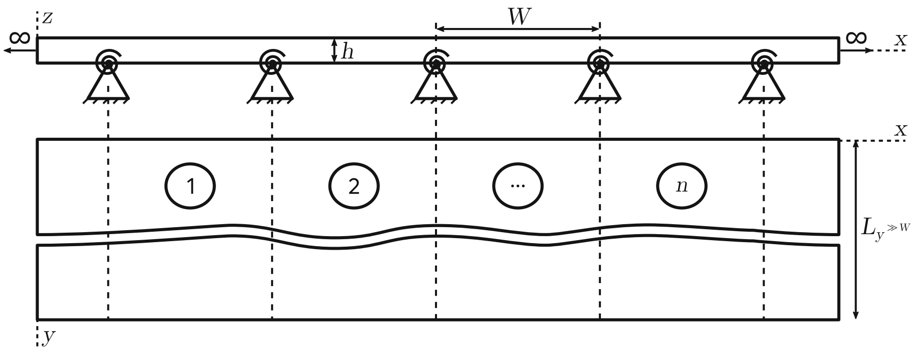

Fig. 1. Plate bounded by a set of equidistant ribs forming n areas which theoretically behaves like narrow-plate bounded on their longer edges to a rigid frame.

bending moments (represented by rotation spring in Fig. 1) to their neighboring beam portions. In such systems, vibrations propagate from one portion to another through bending moments produced at the junction between two portions. Mead [6] has shown that for frequencies bellow the first resonance of an individual portion, the propagation from one portion to another attenuates exponentially. This means that in our system, the cut off frequency f_1 that marks the transition between propagative and evanescent waves along the waveguide dimension, also corresponds to the transition from propagative to evanescent wave in the transverse dimension. This enables the extension of the waveguide approach describes in [1] to 2D surfaces regularly supported by thin ribs.

2.2 Evanescence and Waveguide Geometry

The localization along the y-axis of low frequencies is implied by the waveguide geometry of the propagation medium. In such medium, it was shown that bending waves cannot propagate below the cut-off frequency of the first propagation mode. This non-propagation effect allows the confinement of vibrotactile stimuli and thus can be used for multitouch haptic interactions. If we suppose a perfect bounding of the ribs to a rigid frame, each of the n areas possesses their first cut-off frequency equal to [1]:

$$f_1 = \frac{\pi}{4\sqrt{3}} \frac{h}{W^2} \sqrt{\frac{E}{\rho(1-\nu^2)}} \tag{1}$$

with ρ the mass density, E the Young's modulus, ν the Poisson's ratio, h the plate thickness, W the distance between ribs. When an area is submitted to a vibration of frequency $f < f_1$, waves propagating along the y-axis and the x-axis are evanescent and dies exponentially with the distance.

3 Experimental Validation

3.1 Apparatus

To verify the spatial localization provided by our method, we have set up a system designed to allow a user to freely explore a surface. The size of the device thus corresponds to the size of an adult hand, and the number of areas formed corresponds to the number of fingers. The only requirement associated with the implementation of this method is having a plate correctly bounded periodically to a rigid frame. If each created area have a waveguide geometry, a cut-off frequency exists and a localized vibration can be obtained.

Mechanical Components. The apparatus consists in a glass plate, measuring $150 \times 130 \times 0.5\,\text{mm}^3$, bounded on a set of 6 equidistant ribs of width 4 mm forming 5 areas. In order to provide haptic feedbacks, piezoelectric actuators (muRata 7BB-20-3) of circular geometry, composed of two part: a plate of diameter 20 mm, thickness of 0.1 mm; and a piezoelectric transducer of diameter 12.8 mm, thickness of 0.11 mm, were glued on the bottom side of the plate between each ribs. The out of plane displacement of the surface is measured by a laser vibrometer (Polytec MLV-100/OFV-5000) mounted on a motorized 3 axis platform. This setup is illustrated on Fig. 2.

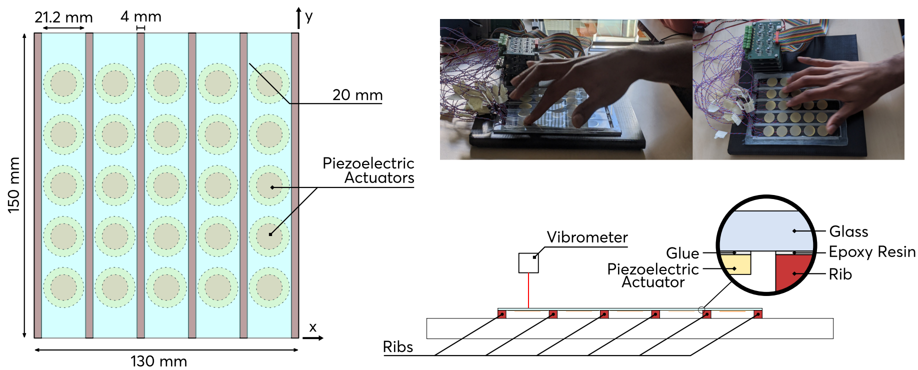

Fig. 2. Experimental setup. A glass plate is bounded onto a set of 6 equidistant ribs with epoxy resin. The actuators are glued to the bottom of the plate, 5 per area between each rib, for a total of 25 actuators.

Driving Components. Because vibration localization is induced by the propagation medium geometry, no specific calculation nor wave control implementation are needed. Signal amplification for each actuators was assured by a Piezo Haptics Driver DRV8862 from Texas Instrument. A voltage output module NI-9264 was used to send requested analog signals to each driver for amplification.

Communication with the NI-9264 voltage output module and signal design was made with Python using the PyDAQmx package.

3.2 System Frequency Response Function (FRF)

The frequency response function or FRF (ratio of the displacement at a given point to the voltage applied to an actuator in the frequency domain) for the actuator was measured by sending a linear sweep signal of 40 V amplitude going from 0 Hz to 5 kHz sampled at 10 kHz and is represented on Fig. 3. We search with this FRF frequencies where the amplitude at the center of the actuator (in light gold) presents noticeable differences with the amplitude outside the actuator area (in dark blue). We can notice that, from 0 to 1.2 kHz, vibration amplitudes inside the actuator area are 30 dB higher in average than outside the actuator area which shows that elastic waves do not propagate throughout the plate for vibration frequency in this range. The FRFs at other points were also measured and show the same behavior, though with some differences. We supposed in Sect. 2 that clamping conditions were perfect thus having the same cut-off frequency for every area. But the FRF in other areas actually present different cut-off frequencies meaning that the clamping quality of each rib was not assured. The boundary condition being made with epoxy resin we can assume that eventual air bubbles or gaps could have been left during the mounting process thus giving slight behavior differences between each area and locally within each area.

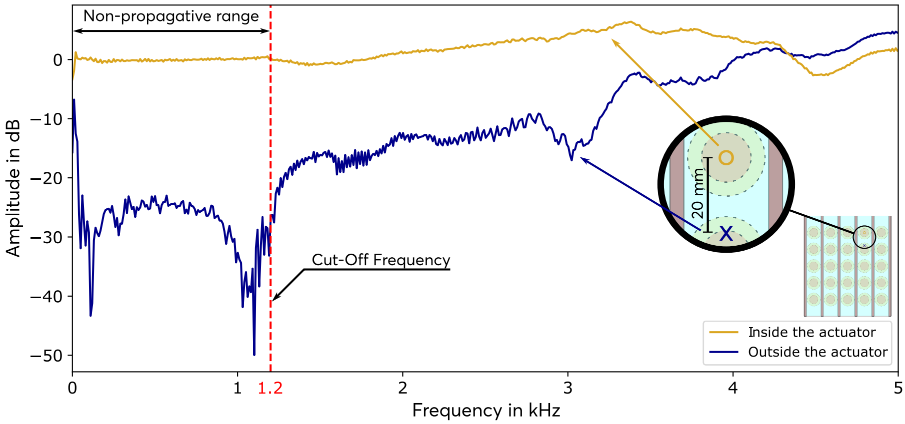

Fig. 3. System Frequency Response Function (FRF) $H_{dB} = 20\log_{10}|H|$ at the center of the activated actuator (in light gold) and 20 mm away outside the actuator inside the same area (in dark blue). (Color figure online)

3.3 Stimuli Confinement

To illustrate the multitouch capability of our device we mapped plate amplitudes when submitted to signals sent with multiple piezoelectric actuators. We chose a 250 Hz (tactile sensitivity peak) 5 cycles burst excitation and a driving voltage amplitude of a 100 V for every actuator used. Figure 4 shows the maximum displacement throughout the plate when using 1, 2, 3, 5, 6 and 7 actuators at the same time. We can notice that waves are confined above activated actuators with amplitudes reaching 3 µm inside the actuator area. Outside the actuated area, waves propagating along the y-axis are evanescent and die exponentially. Along the x-axis, vibration propagation is impeded by the clamped ribs surrounding the actuator. The energy representation with a logarithmic scale of Fig. 5 shows certain areas of interest. Apart from localized energy area above each actuator, we can note leaks with a 15 dB amplitude difference between vibrations inside actuator areas and leaked vibrations while other areas present a 30 dB difference. This leak is actually due to clamping imperfection caused during the prototype assembly. Another area which is less visible (squared in green in Fig. 5), asses the evanescent behavior along the x-axis due to the set of supports. This important loss of energy (around 25 dB loss) comes from the evanescence behavior and the width of the ribs which, by providing strong bending moments, reduce the transmitted energy. Thinner ribs would still provide a localized effect but with a reduced energy loss.

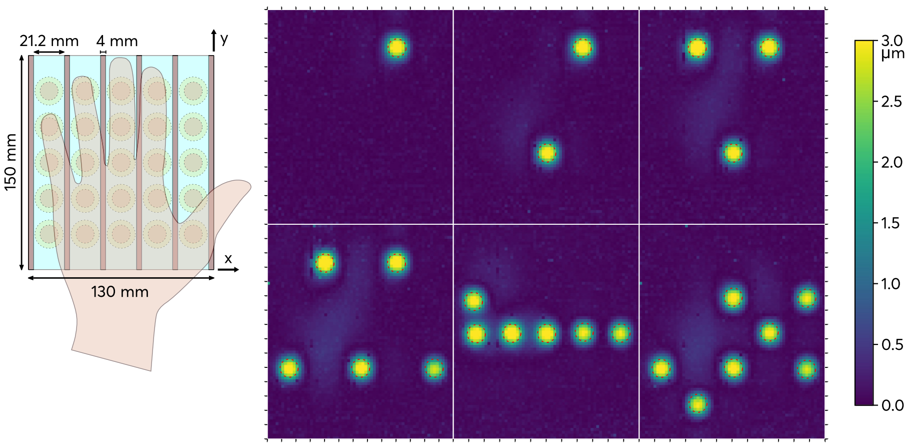

Fig. 4. Maximum out of plane displacement in μm of the plate for 1, 2, 3, 5, 6 and 7 actuators activated at same time. Vibration sources are localized and reach a vibration amplitude above 3 µm while the rest of the plate stays at rest.

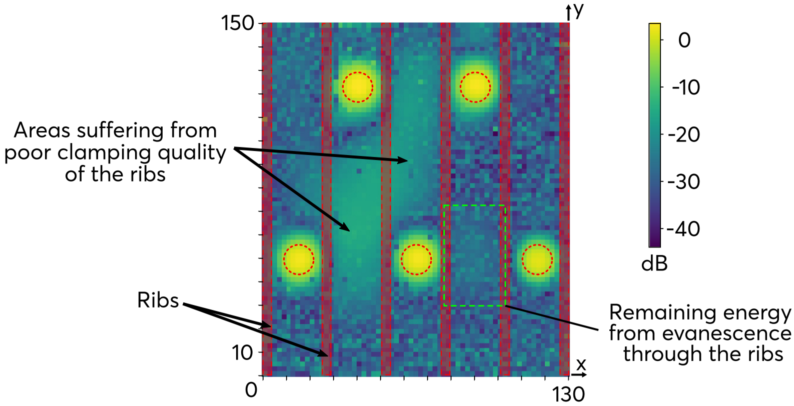

Fig. 5. Energy representation with a logarithmic scale of the plate submitted to 5 activated actuators. Most of the energy is localized above each piezoelectric actuator.

4 Discussion and Perspective

The device shown here can provide localized vibrotactile feedback in several areas of a continuous plate. The confinement is achieved along both axis by low frequency evanescence phenomenon: one based on the geometry of the propagation medium; the other based on the periodically placed supports. This system is particularly unique and there is to our knowledge no setup with such capabilities and we believe that our device offers new possibilities for studying the tactile perception and to develop new interactions. The interface is simple and robust, i.e. it does not require any special signal processing or computation to work and is not impacted by user interaction. However, since evanescent waves are used, the localization of stimuli is only done in the area of each actuator. In order to increase the resolution of such a device, the number of actuators must be multiplied as well as the number of ribs. It raises questions about the control electronics, the power consumption and the available amplitude (sufficient amplitudes cannot be guaranteed with small actuators). Another point that can also be addressed is concerning possible use case of such device. The authors believe that the method in question is easily applicable to medium to large surfaces such as car dashboards. Breitschaft and al. [2] indicates that in the automotive domain four tasks must be performed by tactile interiors: exploration, detection, identification and usage. These tasks are already achievable as is if the method is applied to a thin touch screen ($<$2 mm). The user can explore the surface freely with one or more fingers or by sliding or tapping or even by placing his hand entirely on the surface without changing its behavior. The detection of the localized stimulus and its identification is ensured by the shape and frequency content of the signal used, which can also be varied according to the position of the fingers if one wants to create areas with different vibratory behaviors. Finally the confirmation action is done by the selected zone by sending a signal with a strong frequency dynamic to simulate a button (this function can be improved by adding a force sensor). Future works will focus on two axes, one dealing with the possibility of thinner ribs and the other on an interface use case, in particular the localization of a vibratory targets on a flat continuous surface.

5 Conclusion

At low frequency, bounded ribbed-plates allow for the localization of vibrotactile stimuli. A piezoelectric actuator bounded to such medium mostly produce evanescent waves which are confined to the actuator covered area as long as the driving frequency is lower than the first cut-off frequency of our system. No control strategies nor signal processing are needed, directly sending the desired signal to the desired actuator suffice in order to obtain a localized vibrotactile stimuli. Multitouch and multiuser interactions can therefore be implemented with ease. Application such as tactile fingerspelling [3], tactile keyboard, tactile memory games and applications using exploratory procedures on a plates can be implemented here. Although the presence of actuators underneath the plate limits applications to surfaces where transparency is not necessary, recent breakthroughs shows that transparent piezoelectric actuators are at hand [9] making our technology compatible with screen surfaces.

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