

A NEW TECHNIQUE FOR THE CONTROLLED STIMULATION OF THE SKIN

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ABSTRACT

Traditional methods of skin stimulation for psychophysical, neurophysiologic studies and other investigations involve the use of indentation. We will describe an apparatus intended to cause skin tangential deformation in a controlled manner, which is motivated by much recent evidence suggesting that such stimulation is both behaviorally and physiologically relevant. What the apparatus does is to contact the skin at two locations separated by a distance of about one millimeter, and stretch and compress it by using piezoelectric benders. The mechanical behavior of the skin at this scale is not quantitatively known. We designed the lateral skin stimulator to have a programmable mechanical impedance. This enables us to test the response of the skin mechanically, behaviorally and neurophysiologically with a wide range of conditions.

INTRODUCTION

A tactile display provides humans with information through the sense of touch like a CRT provides optical information through the sense of vision. Piezoelectric bimorph benders have been initially used in tactile displays to tangentially stimulate skin (Pasquero and Hayward, 2003). Although the tangential deformation of the skin could cause more perceived intensity of stimulation than normal deformation in the certain area of the skin (Biggs and Srinivasan, 2002), the peak displacement and peak force of the piezoelectric benders are limited due to the intrinsic weakness of the cantilevered structures which rapidly lose stiffness with length. As a result, when a bender is loaded by the skin of the finger-tip, deflection is limited for any design: a long bender is too soft and a short bender does not deflect sufficiently.

The biomechanics of the skin and of the subcutaneous tissues is fundamental for the engineering of tactile displays. Although the relationship between the skin deformation and the perceived touch sensation of touch is still not completely known, recent studies show that the lateral deformation of the skin can produce substantial tactile sensations (A.M. Smith, 1996) (Birznieks I., 2001) (Pare, 2002). Our review of the literature did not reveal any prior studies that explore the lateral mechanical behavior of the skin at a sub-millimeter level.

Therefore, a programmable sub-millimeter skin stimulator would be a valuable contribution to this research field.

In this paper, we introduce a new apparatus that is designed to stimulate the skin in a controllable manner. This device employs an adjustable structure able to trade deflection and force while adjusting its mechanical stiffness. This apparatus was used to experimentally search for an optimal compromise between stiffness and deflection by maximizing the perceived tactile intensity using an adaptive method. In the future, the same apparatus could be used to investigate the biomechanical model of the skin at a sub-millimeter level by adding a laser deflection measurement kit.

METHODS

1. System Setup

Referring to Figure 1, two piezoelectric bimorph benders (Y-poled bender T215-H4-303Y from Piezo Systems Inc.) that are supported at two points; one at the feet of the benders and the other at an intermediate position. The free deflection and the stiffness depend on the distance from the upper support to the tip of the bender, hence, the mechanical impedance can be adjusted by changing the position of the intermediate support. A position sensor (Model 602, Duncan Electronics Inc.) is connected to the adjustable support to read its position and feed it to a computer (Pentium III 500MHz) via an A/D channel. Two D/A channels drive two high voltage amplifiers ($\pm 120V$ DC) to activate the benders.

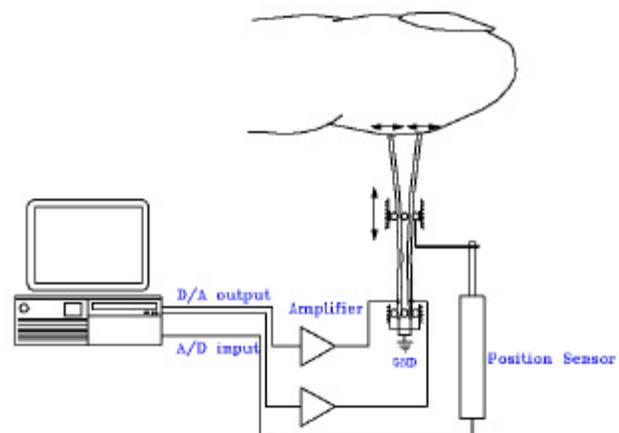


Figure 1. System diagram

2 Constituent Equations

The constituent equation of a cantilever piezoelectric bender subjected to an external force were given by Jan Smits as follows [1]:

$$\mathbf{d} = \frac{L^3}{2Ewh^3} \cdot F^E - \frac{3d_{31}L^2}{8h^2} V \quad (1)$$

In our two-support structure, the strain equations of a bimorph piezoelectric bender are given in [1]:

$$\frac{F}{Ewh} + \frac{hM^U}{2EI^U} - d_{31}E_3 \quad (2)$$

$$= -\frac{F}{Ewh} - \frac{hM^L}{2EI^L} + d_{31}E_3$$

$$\frac{1}{R^U} = \frac{1}{R^L} = \frac{M^U}{EI^U} = \frac{M^L}{EI^L} \quad (3)$$

$$M^U = M^L = \frac{F \cdot h}{2} \quad (4)$$

Where the E is the Young modulus of the piezoelectric material; the h is the thickness of the upper and lower beam; the w is the width of the piezoelectric beam; the E_3 is the electric field to activate the piezoelectric bender; the d_{31} is the piezoelectric strain coefficient. Therefore:

$$M^U = M^L = \frac{d_{31}E_3wh^2E}{8} \quad (5)$$

From the basic differential equation governing the deflection of beams, we get:

$$EI^U \frac{d^2y}{dx^2} = M^U = \frac{d_{31}E_3wh^2E}{8} \quad (6)$$

Consequently,

$$\frac{d^2y}{dx^2} = \frac{3d_{31}E_3}{2h} \quad (7)$$

By directly integrating both sides,

$$y(x) = \frac{3d_{31}E_3}{4h} x^2 + C_1x + C_2 \quad (8)$$

Since the boundary conditions are

$$y(0) = 0 \text{ and } y(l_1) = 0$$

The C_1 and C_2 can be determined as

$$C_1 = -\frac{3d_{31}E_3}{4h} l_1 \text{ and } C_2 = 0.$$

Therefore,

$$y(x) = \frac{3d_{31}E_3}{4h} x(x-l_1) \quad (9)$$

When a piezoelectric beam subjected to an external force F^E , the total energy stored in the beam is:

$$U = \int_0^{l_1+l_2} \int_0^w \int_{-h/2}^{h/2} u^U dx dy dz + \int_0^{l_1+l_2} \int_0^w \int_{-h/2}^{h/2} u^L dx dy dz \quad (10)$$

Where u^U and u^L , shown as follows, are energy density in the upper beam and lower beam respectively.

$$u^U = \frac{1}{2E} (\mathbf{s}^U)^2 - d_{31}E_3 \mathbf{s}^U + \frac{1}{2} \mathbf{e}_{33}^T E_3^2 \quad (11a)$$

$$u^L = \frac{1}{2E} (\mathbf{s}^L)^2 + d_{31}E_3 \mathbf{s}^L + \frac{1}{2} \mathbf{e}_{33}^T E_3^2 \quad (11b)$$

Where \mathbf{s}^U and \mathbf{s}^L are the stress of upper and lower beam respectively; the \mathbf{e}_{33}^T is the permittivity at constant stress.

The bending moment M^E caused by an external force F^E of a two-support beam is shown in figure 2.

$$M^E = \begin{cases} \frac{l_2 F^E}{l_1} x & 0 \leq x \leq l_1 \\ F^E * (l_1 + l_2 - x) & l_1 \leq x \leq l_1 + l_2 \end{cases} \quad (12)$$

The stress of the upper beam is:

$$\mathbf{s}^U = -\left(-\frac{1}{4} d_{31}E_3E + \frac{3d_{31}E_3E}{2h} z + \frac{M^E}{I} \left(z + \frac{h}{2}\right)\right) \quad (13a)$$

Similarly, the stress of the lower beam is:

$$\mathbf{s}^L = -\left(-\frac{1}{4} d_{31}E_3E + \frac{3d_{31}E_3E}{2h} z + \frac{M^E}{I} \left(z - \frac{h}{2}\right)\right) \quad (13b)$$

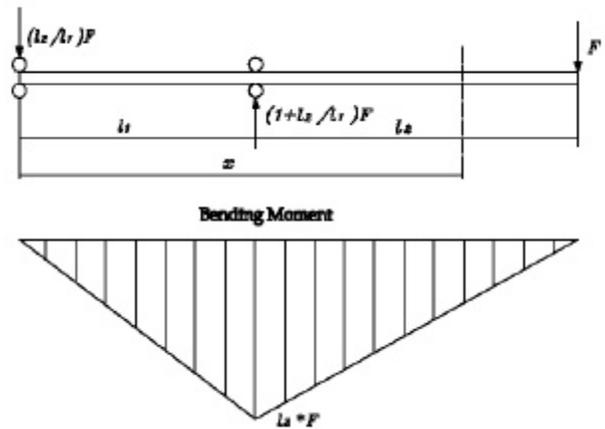


Figure 2. The bending moment of a two-support beam

According to equation 10, the total energy stored in the bender is:

$$U = whd_{31}^2(l_1 + l_2)(e_{33}^2 - \frac{1}{4}d_{31}^2E) + \frac{l_2^2(l_1 + l_2)}{4Ewh^3}(F^E)^2 + \frac{3d_{31}^2E_3}{4h}(l_1 + l_2)l_2F^E \quad (14)$$

Using the energy method, we find the constituent equation of the piezoelectric bimorph bender under an external force as follows:

$$\begin{aligned} \mathbf{d} &= \frac{\partial U}{\partial F^E} = \frac{l_2^2(l_1 + l_2)}{2Ewh^3}F^E + \frac{3d_{31}E_3}{4h}(l_1 + l_2)l_2 \\ &= \frac{l_2^2(l_1 + l_2)}{2Ewh^3}F^E - \frac{3d_{31}V}{8h^2}(l_1 + l_2)l_2 \end{aligned} \quad (15)$$

Comparing equation 1 to equation 15, we find that the free deflection of the structure that we used is

$$\mathbf{d} = \frac{3d_{31}V}{4h^2}l_2(l_1 + l_2)$$

For a cantilever beam to achieve this same free deflection, the length of that beam should be

$$l' = \sqrt{l_2(l_1 + l_2)}.$$

Therefore, its stiffness would be

$$\frac{F^E}{\mathbf{d}} = \frac{2Ewh^3}{(l_2(l_1 + l_2))^{3/2}}$$

which is less than the stiffness of this structure

$$\frac{2Ewh^3}{l_2^2(l_1 + l_2)}.$$

In other words, for a cantilever beam to achieve the same stiffness with that of the proposed structure, its free deflection will always be smaller than that of the proposed structure. This is represented in the figure 3.

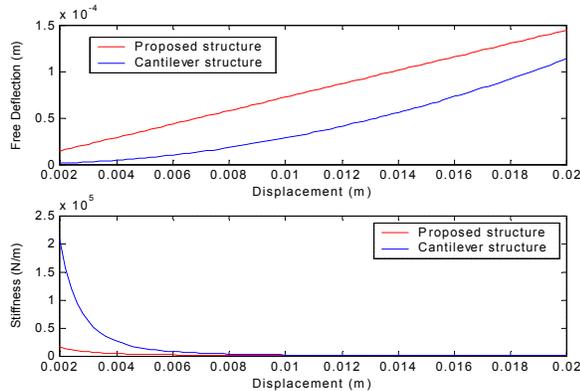


Figure 3. Comparison of the cantilever structure and the proposed structure

3 Experiment

Stimulus: To approximate better the conditions under which a tactile display could be used, a non periodic stimulation signal was selected. It consisted of a sequence of pulses shaped like the differential of a Gaussian with a duration of 0.5 seconds separated by time intervals randomly varying from 0.2 to 1.5 seconds.

Subjects: Six healthy, right-handed subjects (2 females and 4 males; ages 22–33) participated in the experiment.

Procedure: At the start of the trials, subjects were seated comfortably in front of the apparatus, and had their index gently resting on the top of the benders. During the trials, the computer was continuously sending pulse signals. The magnitude of the pulses was controlled by the subjects by pressing the up-arrow key, if they want to increase magnitude, or the down-arrow key if they want to decrease magnitude. The upper support was set to 5 positions sequentially. At each position, the subjects are asked to find the minimum magnitude of the pulses that they could feel.

RESULTS

Figure 4 illustrates the minimum intensities that make the subjects feel the stimulation at five positions. Psychophysical experiment data show that at the position 2, which is 6 millimeters from the tip, the minimum intensity needed to cause a tactile sensation is smallest. This finding suggests that an optimal length exists for piezoelectric benders used in tactile displays based on lateral skin deformation. This result is probably a consequence of the fact that the deflection reaches its peak at this particular position.

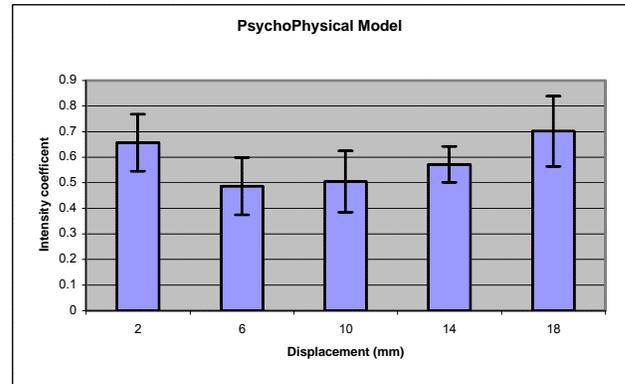


Figure 4. PsychoPhysical experiment result

DISCUSSION

Many factors in the stimuli pattern such as waveform shape, duration, spectral content, intervals of repetition and so-on could affect the tactile sensation. For example, we found that a smooth pulse signal plus a small magnitude white noise (10% of the of the clean signal) could cause the tactile sensation to be several times stronger than that given by the clean signal, although the difference between their power spectrum is around 10%.

CONCLUSION

This very preliminary study encourages us conduct more systematic behavioral studies to investigate the factors that affect human perception of tactile sensation by stretching the skin. In addition, a laser measurement kit used to directly measure the actual deflection will be added to the apparatus. It will then be possible to explore detailed biomechanical models of the skin clarify the mechanical behavior of the finger pad skin at a sub-millimeter level. It will then be possible to relate known micromechanical stimuli to perceptual response.

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