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Vibro-tactile displays for stimulating surface impressions

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ABSTRACT

Nowadays, information transmission devices, which activate the human tactile sense, are commonly available for Braille generation to support the blind and on the enhancement of the gaming experience with a vibrating gamepad. The generation of real surface structures with a device, a so-called tactile display, has not been solved satisfactorily so far. A new approach is to generate a stress-strain-distribution in the finger similar to that, which occurs while moving a finger over a surface, so that the tactile perception is alike. Vibrations generate the stress-strain-distribution. To realize this in a tactile display, interdisciplinary knowledge is necessary. The actuators of the display have to address the different stimulation processes of the individual mechanoreceptors in the skin. In addition, every person has individual tactile impressions according to the fingers physiology. In order to satisfy this requirements, small, powerful and high dynamic actuators are needed. Furthermore, the current load characteristic of the actuator is always needed for control. In this work, our novel tactile displays to stimulate the mechanoreceptors of the human finger by suitable frequencies and amplitudes are discussed in detail. The self-sensing concept is presented to obtain online the individual actuators displacement and force.

Keywords: Tactile display, self-sensing, transfer matrix method, perception threshold

1. INTRODUCTION

Today, there is already a broad spectrum of displays in the scientific world that can be understood as tactile displays and use the tactile sense of the human being as the main communication channel. Such displays promise a high potential, if their functionality can be realized cost-effectively in the future. This not only includes the enrichment of the gaming industry, but also online shopping platforms could offer a better shopping experience if buyers had such devices at home. Also, the training of assembly staff could be made much more realistic through VR (Virtual Reality) trainings, which lead to a higher learning success. In order to be able to develop such displays, a sound knowledge of the sense of touch is required. While it is sufficient to use an actuator distance equal to the two-point threshold for the representation of static Braille information, the actuator distance must be smaller than the two-point threshold for displays that want to simulate a real surface. In [14], Bensmaïa et al. showed that this distance should be between 1 mm and 2 mm so that the individual pins are no longer recognized. In addition, the functions of the individual mechanoreceptors of the cutaneous somatosensory system of the human skin must be known. As indicated in [15], there are the Meissner corpuscle, which are sensitive to the speed of perception. They operate in a frequency range of about 1 Hz-300 Hz and are mainly responsible for motion detection and grip control. They require amplitudes of at least 6 µm. The Merkel receptors are sensitive to static and perpendicular deflection to the finger. They are intend for shape and texture perception and operate in a frequency range from 0 Hz to 30 Hz. They require amplitudes of at least 30 µm. The Ruffini corpuscle, are sensitive to tangential forces and skin shearing. They operate in a frequency range from 0 Hz to 15 Hz. They require amplitudes of at least 300 µm, which is a major reason why many tactile displays do not activate these corpuscles. Finally, there is the Pacinian corpuscle. They are especially sensitive to

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vibrations and they provide the fine tuning of sensations. They operate in a frequency range from 5 Hz to 1000 Hz and require only amplitudes of at least about 0.08 µm. With this kind of background information tactile displays can be developed. A possible classification of different tactile displays can be carried out as suggested in [1]: There are three main groups of tactile displays: 1. Simulation of physical characteristics 2. Stimulation of mechanoreceptors 3. Activation of mechanoreceptors. For the first group, a deeper knowledge about the physical properties of the surface that is simulated is necessary in contrast to the understanding of the sense of touch; for the other two groups, a high understanding of the tactile sense itself is necessary. The boundaries between the simulation of physical properties and the stimulation of mechanoreceptors are vaguely, so that the first and second group can be better classified with their objectives. For the first and second group the objectives are to transmit Braille information, to reproduce surface textures, to adjust the resistive force and to control the temperature. To transmit Braille information, the achieved actuator type systems are pneumatically in [2], with phase change liquid gas in [3], with a smart fluid with an electrically controllable viscosity in [4] with an electrical actuation of a polymer in [5] and a static deformation of piezoelectric bending actuators in [6] or piezoelectric multilayers in [20] are driven. To transmit surface texture information the achieved actuator types are pneumatically [7, 16], with shape memory alloy in [8, 17], with electrostatic force in [9, 18], with polymer actuators in [10] and with electro magnetic force in [11, 19]. For the area of the resistive force the authors in [12] developed a stiffness controllable display. The authors in [13] published a temperature changeable display which uses different spread of gases out of nozzles e.g. ethanol. For the third group Kitamura and Miki developed in [21] an electro tactile display with needles, which stimulate directly the mechanoreceptors via an electro stimulus. We propose a further category of tactile displays. These displays stand out due to their high frequency range up to 1 kHz. The developers of these displays do not want to reproduce the real surface with its physical properties as accurately as possible. The main goal is rather to stimulate the finger with vibrations in such a way that the same feeling arises as when driving over a surface with the finger without the real surface being present. This is because when a finger passes over a surface, the finger's papillaries on the surface to be touched constantly cause the finger to stick and glide, causing the finger to vibrate which creates the sensation of feeling. Therefore, the tactile displays should create a similar stress and strain distribution in the finger like with a real surface contact without the real surface (see figure 1). Examples for such kind of displays are for a one-excitation direction actuators is the tactile display called STReSS [22] and the solid-state joint actuator [23]. These kinds of Displays make a step further and the developers designed displays with 2D excitation actuators like in [22] with the STReSS² where the actuators are circular positioned and in [15, 24] with real 2D excitation directions one perpendicular to the finger an one for shearing excitation. In order to adjust the actuators to the corresponding amplitudes, frequencies and forces offered by human finger physiology, preliminary investigations are necessary. For this purpose, impedance measurements are performed on the fingers of several subjects using pins with a similar geometry to the later actuator. Based on these measurements, the actuators are then developed and designed. The transfer matrix method [25, 26] has proven to be extremely fast for the description of the motion, especially in piezoelectric bending actuators. So this method is used here for the description of the actuators. It is also possible with this method to use the actuator itself as a sensor online via the so-called self-sensing in order to be able to control the load online [27]. In this publication, we will discuss in detail the achievements of our vibro tactile displays from design to modelling to the finished display. We will present the novel displays with a 1D line of actuators like e.g. from [23]. Afterwards we will present a novel display in which the actuators are distributed in a 2D area and consist only of bending actuators, then the coupled actuators with two excitation directions distributed in a 2D area of the novel display of [15].

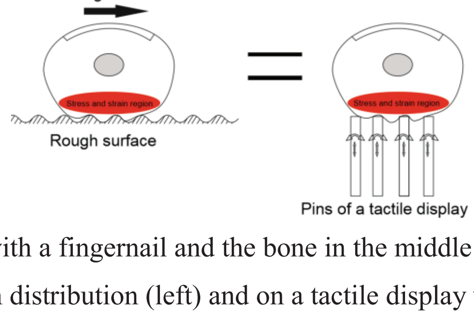


Figure 1 – A schematic finger with a fingernail and the bone in the middle moves over a rough surface and the resulting stress and strain distribution (left) and on a tactile display with moving actuators (right)

2. LOAD MODEL AND PERCEPTION THRESHOLD

In this section, the different load models for the individual tactile displays are presented, on the basis of which the actuators are then designed. Currently, a separate load model is created for each upcoming contact geometry, because it has turned out that every small change with the contact area has an influence on the feeling experience. So it makes a difference whether the subject press on the actuator with 2 g or with 50 g. Furthermore, it makes a difference whether the actuator surface is small or large, round or angular. Also an influence possesses a possibly existing mask on which the finger rests and actuators are led only through. In order to create a uniform load model, extensive, very complex simulations would be necessary, whereby the parameters for these simulations are not easy to obtain, because every person has a slightly different finger and different emotional perception. Therefore, it is currently unavoidable to carry out studies on subjects to ensure that the actuators manufactured later also fulfill their purpose. The lowest limit that the actuators must reach under load conditions with their deflection amplitudes is the perception threshold. From this threshold, the subjects are barely able to feel that something is there. Better are amplitudes that are larger than the perception threshold.

2.1 Load model

In [25] we show how a real actuator (in this case a piezoelectric bimorph) is measured with a LASER vibrometer (see figure 1, left). The actuator is placed on a load cell and the finger lies on the mounting system of the actuator. In the mounting system is an aperture of 2 mm x 3 mm, where the finger has contact with the actuator. Throughout the experiment, the subject were ordered to keep the load on the actuator constant. Six subjects participated in this study and the results of the measurements can be seen in figure 1, middle. It is clearly visible that there is a large scattering of the results and the behaviour is changing with the frequency. We built up a generalized Maxwell model (see figure 1 right) using the measurements results and thus modeled the load of the finger on the actuator for these conditions and we thus determined the optimal length according to the properties of our actuator to arrive against the resistance of the finger. These results were used for the display in section 3.2.

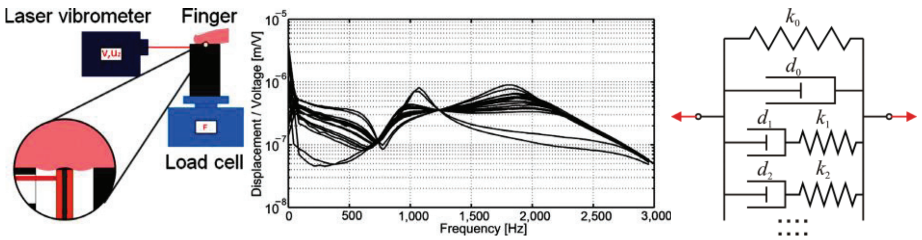


Figure 1 – Schematic representation of the experimental setup (left), Measurement of six subjects (middle), Generalized Maxwell model for the translational load component (right) [25]

For the displays in section 3.1 and section 3.3 the load model were made in a similar way with the difference that displacement has been not measured. It is depicted, in figure 2 left, that the subjects placed their fingers on a pin with a nearly similar contact geometry like the actuator of the later display. The shaker was adjusted in two positions. One for perpendicular and one for tangential excitation of the finger. With an impedance probe the impedance were measured. The subjects had to keep a steady preload of 50 g. Out of theses recorded data a mechanical equivalent model depending on the excitation frequency were modeled as a load model. In detail explanations to the load models can be found in [15] and [25].

Figure 2 – Schematic representation of the experimental setup (left), conversion of a finger to a frequency depending spring damping model (right) [15]

2.2 Perception threshold

The perception threshold of the subjects is strongly dependent on the contact geometry, as well as on the excitation direction and the preload. For this purpose, we measured the perception threshold of several subjects using the experimental setup depicted in figure 2 left and present the medians of the measurement results in figure 3. For vertical excitation, 8 Subjects participated and their average age was 30 years. For the stimulation from left to right 7 subjects took part and their average age was 25 years. 8 subjects took part in the front to back stimulation and their average age was 26 years.

The subjects carried out a preparation test, after which they knew what feeling they had to pay attention to. The amplitude of the shaker was then increased in the experiment until the subjects gave the signal that they could feel something.

The results in figure 3 depict that the perception threshold is frequency-dependent. This is due to the behaviour of the mechanoreceptors. They are also direction-dependent and load-dependent. This is due to a change in the deformation and prestressing state in the finger. These perception thresholds represent the absolute minimum that the actuators must reach in order for the subject to feel anything at all.

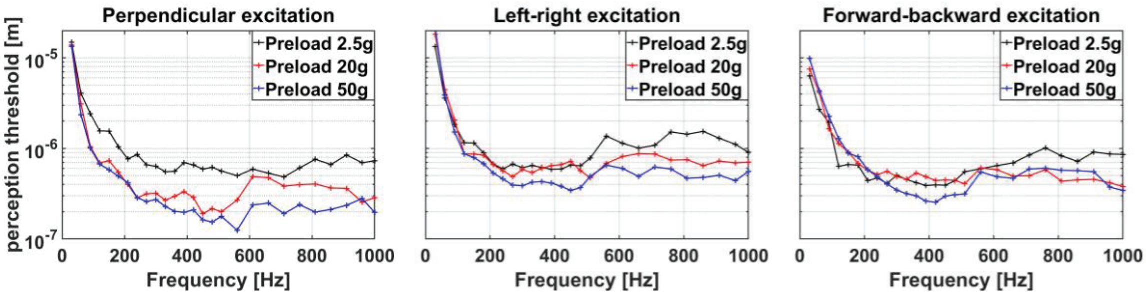


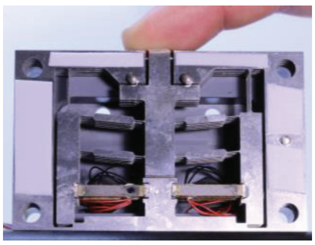
Figure 3 – Median of measured perception thresholds with under different preload of the finger on the actuator

3. TACTILE DISPLAYS

In this section we introduce our tactile displays. We describe the special features and give simplified models with which it is possible to operate these tactile displays. We go from a line display to an array display up to a coupled array display, where the actuators have two excitation directions.

3.1 The line displays

Figure 4 shows two tactile line displays that are intended to compare different excitation directions and actuator types. Five solid state joint actuators are assembled to a display which can be seen in figure 4 left. These are each driven by two piezoelectric multilayers. The contact area to the finger is 9.8 mm x 5.9 mm. Each actuator is only 1 mm thick. The most striking feature of this display is that it can reach deflection amplitudes of up to 100 µm up to frequencies of 500 Hz. A detailed description of this display can be found in [23]. A display were the actuators consist of piezoelectric bimorphs can be seen in figure 4 right. Between the individual layers, the piezoelectric bimorphs are clamped with their contacts in the display and offer the same contact area to the finger as the display shown on the left. With these displays, we pointed out what kind of forces or amplitudes we need in the different excitation directions.



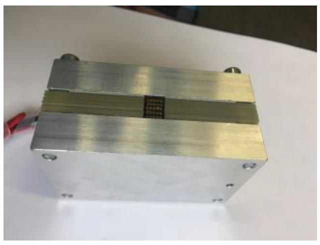


Figure 4 – The perpendicular tactile display with five solid state joint actuators (left) [23], the lateral tactile display with five piezoelectric bimorphs (right)

3.2 Array display

Figure 5 shows a tactile display with a mouse of a computer. In this display the actuators form a rectangular contact area to the finger. The contact surface to the finger has a dimension of 9.5 mm x 7.9 mm. The actuators are arranged in a 5x5 array and can be controlled individually. These actuators are also piezoelectric bimorphs. They are particularly suitable for tactile displays due to their relatively large displacements with sufficient forces in a wide frequency range. On the right in figure 5 the display is shown with the finger of a subject. Due to the area arrangement, complex geometries such as Braille patterns or surface properties can now also be transmitted to the finger with vibrations using shear force excitation.

Figure 5 – The 5x5 Array display with shear force actuators and a PC mouse (left) and with the finger of a subject (right)

3.3 Bimodal tactile display

The bimodal tactile display is made to address the individual mechanoreceptors. The perpendicular actuator works as electromagnetic actuator with low frequencies to stimulate the Merkel receptors. At the top of the perpendicular actuators, piezoelectric bimorphs are mounted as lateral actuators and works at frequencies up to 1 kHz to address the Meissner and Pacinian corpuscles. The bimodal tactile display include 16 coupled actuators in an array of 4x4. The spatial resolution (pin center to pin center) is only 2.4mm with a footprint of each coupled actuator of 2.3 mm x 2.3 mm. In figure 6 a) the lower circuit board of the bimodal tactile display with the 16 perpendicular actuators is shown. They were assembled with an upper circuit board and with the lateral actuators at the base, which can be seen in figure 6 b). In figure 6 c) is the final assembled bimodal tactile display depicted.

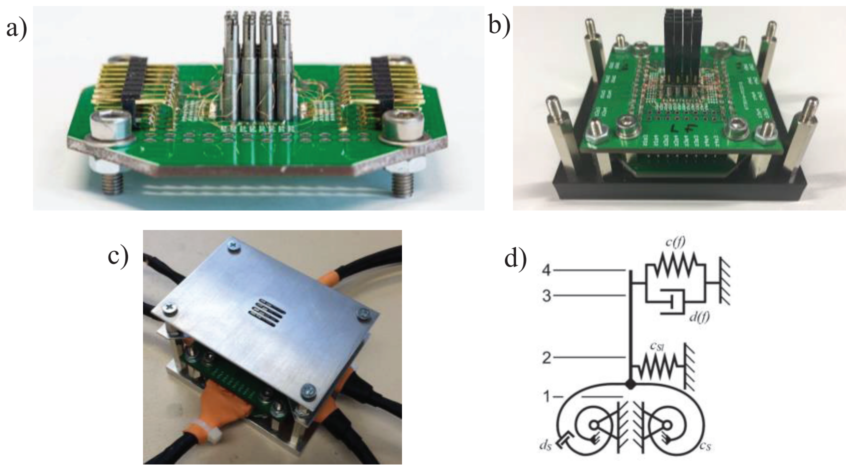


Figure 6 – The bimodal tactile display with a) the perpendicular actuators in the lower circuit board, b) the assembled perpendicular and lateral actuators with the upper and lower circuit board and the base and c) the assembled bimodal tactile display with the mask for the finger. A simplified model of the piezoelectric actuator for the transfer matrix method d)

The transfer matrix method is a well working method to get an efficiently evaluable model of the piezoelectric bimorph. In figure 6 d), the simplified model of the piezoelectric actuator consists of the load model of the finger at the top, the piezoelectric bimorph and the support due to the perpendicular actuator at the lower side, is shown. The equation system for the model consists of three matrices. The third matrix $\boldsymbol{R}_{\mathbf{m}}$ is for the support model, the second matrix $\boldsymbol{A}$ is for the bimorph and the first one is the matrix $\boldsymbol{L}_{\mathbf{m}}$ for the load model of the fingertip:

$$\begin{bmatrix} v_4 \\ \dot{\psi}_4 \\ M_4 \\ F_4 \\ I \end{bmatrix} = \begin{bmatrix} & & & & 0 \\ & & & & 0 \\ & & \boldsymbol{L_m} & & 0 \\ & & & & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \boldsymbol{A} \cdot \begin{bmatrix} & & & & 0 \\ & & & & 0 \\ & & \boldsymbol{R_m} & & 0 \\ & & & & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ \dot{\psi}_1 \\ M_1 \\ F_1 \\ U \end{bmatrix} \tag{1}$$

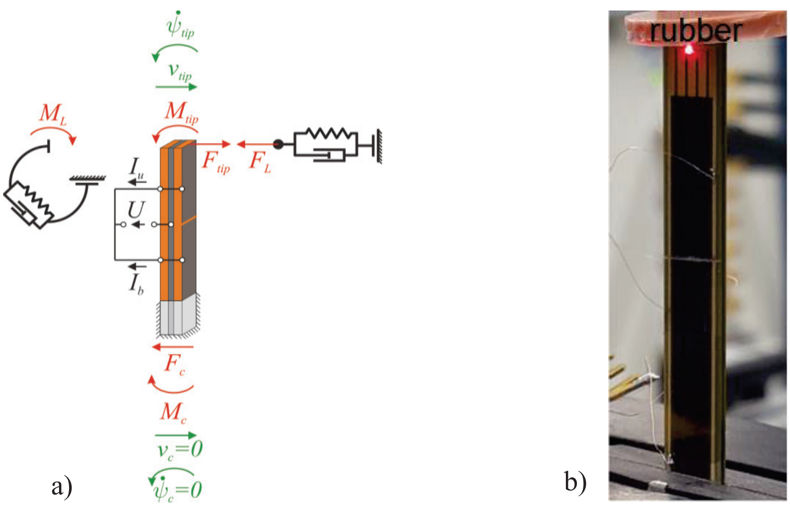
v is the velocity, $\dot{\psi}$ is the angular velocity, M is the moment, F is the force, I is the current and U is the Voltage. The transfer matrices $\boldsymbol{R}_{\mathbf{m}}$, $\boldsymbol{A}$ and $\boldsymbol{L}_{\mathbf{m}}$ were set up as derived in [15]. For a detailed description of the derivation of transfer matrix model and the bimodal tactile display, refer [15].

4. SELF-SENSING

This section introduces the self-sensing concept, which can be used to measure and to control piezoelectric bimorph actuators online.

The transfer matrix method offers a possibility to determine all actual state variables online from the measured current and the given voltage of an operating piezoelectric bimorph. As already shown in equation (1), that a piezoelectric bimorph for its transfer matrix possesses ten state variables coupled by five equations. However, if the current is measured, the voltage is given and the support condition is known, then the transfer matrix can't be evaluate because there are only four variables of ten known. However, if now the contact electrode of the piezo is separated into two parts, then the transfer matrix can be assembled from two coupled systems. The new system then has fifteen state variables, but four of them are known by the coupling, two currents and one voltage can be measured, two variables are also known by the support condition and one voltage is also known due to the coupling. The variables with the m as index are the coupling state variables in the transfer matrix system:

$$\begin{bmatrix} v_{\mathrm{tip}} \\ \dot{\psi}_{\mathrm{tip}} \\ M_{\mathrm{tip}} \\ F_{\mathrm{tip}} \\ I_{\mathrm{u}} \end{bmatrix} = \boldsymbol{A}_{\mathbf{u}} \cdot \begin{bmatrix} v_{\mathrm{m}} \\ \dot{\psi}_{\mathrm{m}} \\ M_{\mathrm{m}} \\ F_{\mathrm{m}} \\ U \end{bmatrix} \qquad \begin{bmatrix} v_{\mathrm{m}} \\ \dot{\psi}_{\mathrm{m}} \\ M_{\mathrm{m}} \\ F_{\mathrm{m}} \\ I_{\mathrm{b}} \end{bmatrix} = \boldsymbol{A}_{\mathbf{b}} \cdot \begin{bmatrix} v_{\mathrm{c}} \\ \dot{\psi}_{\mathrm{c}} \\ M_{\mathrm{c}} \\ F_{\mathrm{c}} \\ U \end{bmatrix} \tag{2}$$



a) b)

Figure 7 – a) Transfer matrix model of the piezoelectric bimorph actuator with the state variables, b) experimental setup to evaluate the self-sensing principle with a piezo electric bimorph

The transfer matrices $\boldsymbol{A}_\mathrm{b}$ and $\boldsymbol{A}_\mathrm{u}$ were set up as derived in [28]. Figure 7 a) shows the model for the transfer matrix calculation with all state variables. Figure 7 b) shows the experimental construction of a piezoelectric bimorph actuator. A measurement with a laser vibrometer serves as reference and the laser light can be seen in figure 7 on the top right of the piezo. In figure 8 the measured admittance can be seen on the left. In figure 8 are the red lines from the reference signal of the laser vibrometer and in green the signals obtained by the self-sensing principle are depicted. In figure 8 b) are the phase signals depicted. A very good agreement between the signals of the laser vibrometer and the self-sensing principle can be seen. Because this method can be used to detect the current state of the piezo online, it is particularly suitable for controlling tactile displays. For more information on the self-sensing principle see [27]. With this segmentation technique (split up the contacts of the piezoelectric bimorph in multiple parts), not only the mechanical state variables can be identified, but also the support conditions if these are unknown or change. The piezoelectric bimorph only has to be divided into four segments.

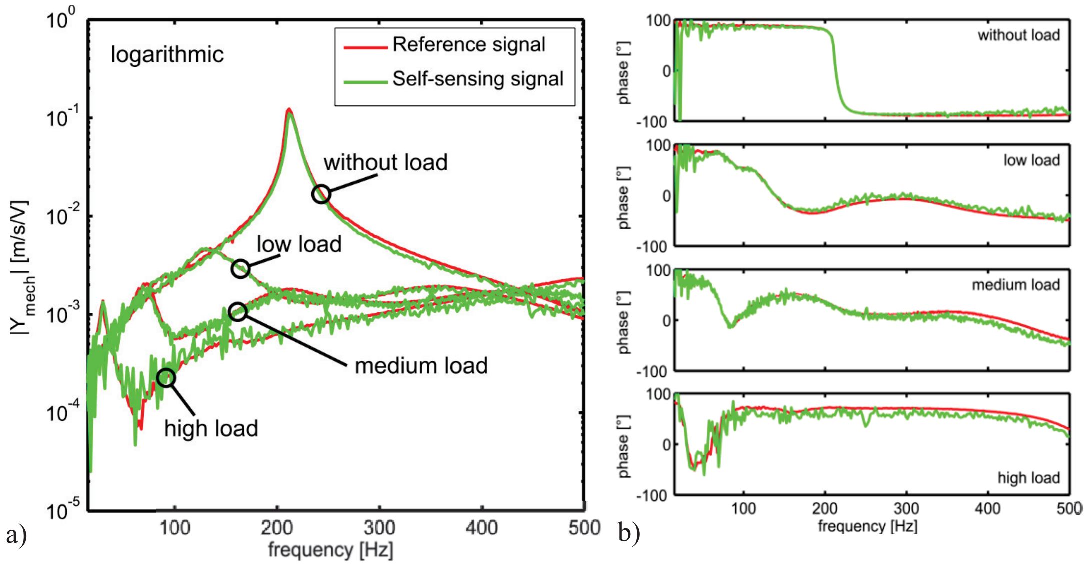


Figure 8 – a) Admittance of the two segmented piezoelectric bimorph with different load, b) phase of the admittance [27]

5. CONCLUSIONS

We have presented several of our novel tactile displays. We showed what kind of preparations it takes to build up a tactile display. This includes the creation of load models based on data from subject studies. By the perception threshold, we have shown which amplitude the actuators of a tactile display must reach at least under load conditions, so that the subjects feel something at all. We have presented our new tactile displays and have provided a method for the description of the actuators with the transfer matrix method. By the self-sensing principle, it is possible to control the piezoelectric bimorphs online and to record their status. We are taking a big step into the future with these new and innovative tactile displays and control concepts.

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