Remote Measurement of Surface Compliance Distribution Using Ultrasound Radiation Pressure

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ABSTRACT

In this paper, we propose a remote measurement system of surface compliance distributions for haptic broadcasting. Our system is composed of an ultrasound phased array generating acoustic radiation pressure on the remote object surface and a laser displacement sensor. The compliance is evaluated by the ratio of the surface displacement to the applied force. We set up a system to examine the feasibility of the method. In the experiments, the distribution of the surface compliance comparable to the human skin was successfully measured for a flat object surface.

KEYWORDS: Remote tactile sensing, Haptic broadcasting, Hardness evaluation, Tele-existence.

INDEX TERMS: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Sharing haptic information of real objects among people should be called Haptic Broadcasting, as shown in Figure 1, and is an attractive challenge in haptics. Conventional haptic tele-existence systems have assumed one-to-one communication between a slave hand and a haptic display, where the slave's motion is faithful to the user's motion and the haptic display duplicates the haptic interaction between the slave and the object. In the system, it is unnecessary to know the whole elasticity model of the object in advance.

On the other hand, if millions of people want to touch an object at the same time, the above mentioned master-slave model fails since millions of slave hands cannot touch the object simultaneously. Thus, producing the whole physical model including elasticity, texture, and other haptic properties of an object is necessary when multiple users share haptic reactions. Our goal is to provide a method to obtain the haptic model of an unknown object instantaneously, for realizing haptic broadcasting of real objects. MacLean has also proposed the model-based approach in [1]. In this paper, we consider required specifications for the haptic broadcasting system and propose a method for sensing haptic properties of an object, especially a surface compliance distribution.

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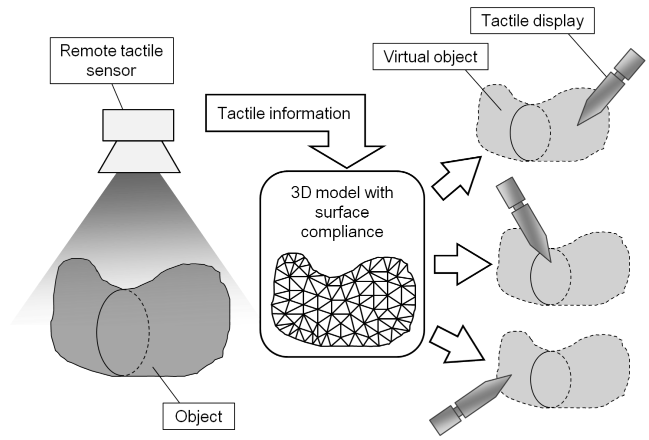


Figure 1. Conceptual image of haptic broadcasting system.

In this paper, we propose a remote measurement system of a surface compliance (elasticity) distribution. This is one of the essential haptic properties. We optically measures the surface vibration induced by airborne ultrasound radiation pressure produced by an ultrasound phased array. The phased array device used in this paper is identical to the tactile display device used in [2]. We estimate the compliance by using the ratio of the surface displacement to the applied spot force of the radiation pressure, assuming the linearity of the elasticity. Since the measurement point can be scanned quickly without any mechanical contact to the object, we can obtain surface compliance at a high frame rate in principle.

All the existing/previous compliance (hardness) distribution sensors need mechanical contact to objects [3, 4] or close placement of an air jet nozzle to objects [5, 6]. Our method is the first example of remote compliance sensor. Although we design the sensing system to provide compliance data for force displays including PHANTOM, the potential applications range widely. For example, we can evaluate the wetness of a painted surface without damaging the surface. It is also applicable to other fragile, very hot, or sticky surfaces. Compliance distribution of a human face is a cosmetically important data. In medical applications, the compliance distributions of various body parts will be useful for finding pathologic tissues and evaluating health conditions.

2 RELATED WORKS

We have a long history of hardness measurement for evaluation of materials. Brinell, Vickers, and Rockwell hardness test [7] are representative methods for evaluating metal materials based on the plastic deformation. For evaluating the compliance of softer materials, there are two approaches of measurement methods; i.e.

direct and indirect measurements. Direct measurement is performed by exerting a force on a surface of an object and by acquiring displacement caused by the force. Compliance at a point is obtained as the ratio of the displacement to the applied force. On the other hand, indirect measurement [8] is performed by observing the resonant frequency or other indirect parameters related to elasticity of an object. In indirect measurement, deriving the static surface reaction needs the viscoelastic model of the object. Our method belongs to the former direct method assuming the linearity of the elasticity.

Generally, for acquiring the compliance distribution by direct measurement, it is necessary to exert active force on an object and to acquire the displacement. One solution in non-contact measurement of the compliance distribution is using air jet to exert a pushing force on the surface of an object [5][6]. A displacement caused by the force was measured by a laser displacement sensor. The air-jet method has the tradeoff between the jet fineness and the jet reach. If we make the force spot diameter comparable to the human finger diameter, the nozzle is required to be placed close to the surface. Thus the jet nozzle must be scanned mechanically keeping that short distance from the object surface to be constant. This limitation makes it not suitable for wide area and high-speed tactile sensing.

Our method realizes the surface compliance distribution measurement from remote positions.

3 PRINCIPLE OF MEASUREMENT

The proposed system consists of an ultrasound phased array and a laser displacement sensor. The ultrasound phased array exerts force on a surface of an object. The laser displacement sensor measures the displacement caused by the force. The distribution of compliance is acquired by scanning both the focal point of the ultrasound beam and the displacement measuring point. This method has advantages that it can exert force on the surface of the object from a remote point and move the exerted force electronically in high-speed.

3.1 Measurand and Assumptions

The proposed system measures a surface compliance distribution from remote positions. We obtain the compliance as the ratio of the surface normal displacement to the applied normal spot force at each point on the surface. The diameter of the spot force is constant. We assume linear elasticity for our measuring object. This assumption means that the compliance which we defined above is constant with applied force.

3.2 Ultrasound Acoustic Radiation Pressure

We utilize a nonlinear phenomenon of ultrasound which is named acoustic radiation pressure to generate a spot force which pushes a surface of an object contactlessly. When an ultrasound wave encounters a surface of an object, it exerts constant pressure on the surface. The magnitude of the pressure is depending on the medium and the object. The pressure P is expressed as

$$P = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where p is the amplitude of the ultrasound, ρ is the density of the medium, c is the speed of the sound, and α is a coefficient determined by the ratio of acoustic impedance between the medium and the object. Since the acoustic impedance of liquid or solid is usually more than 1000 times as great as it of air, the ultrasound is almost perfectly reflected by the boundary surface. In this case, α is nearly equal to 2. Besides, attenuation rate of ultrasound in the air is smaller than that of air jet and the value is typically about 1 dB/m at 40 kHz frequency [9]. Therefore, by using this phenomenon, it is possible to push the surface of the object contactlessly and remotely.

To push the surface with a force spot and scan it, we employ an ultrasound phased array device. It has ultrasound transducers as wave sources. An ultrasound beam is formed by controlling the phase of the wave emitted from each transducer. The beam focuses the ultrasound waves to an arbitrary point in the free space. The diameter of this focal point could be comparable to the wave length. The size of the space in which the focal point can be formed depends on the aperture size of the phased array. Hence the higher the frequency is, the diameter of focal point is smaller. The ultrasound phased array can focus ultrasound beam on a surface of an object and scan the focal point electronically. At the focal point, the amplitude of ultrasound is the summation of the amplitude of each ultrasound from the transducers in the aperture. Therefore there is large pressure by the phased array as the acoustic radiation pressure, which is proportional to the squared amplitude of ultrasound. Using the ultrasound phased array, one can exert concentrated force on an object and the pushing point can be scanned in high-speed, and this is the difference from the approach using air jet.

3.3 Limitation of Proposed System

The measurable range of compliance is determined by the acoustic radiation pressure and the resolution of displacement sensor. Suppose that when the acoustic radiation pressure P is applied on an area A in the surface, which depends on the wave length of ultrasound, and the resolution of the sensor is δ. In this time, measured spring constant is represented as

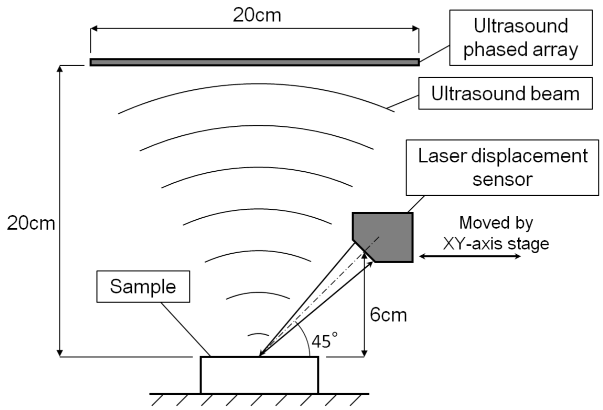
$$k = \frac{PA}{n\delta} \tag{2}$$

where n is an integer that rounded number of the displacement divided by the resolution. Thus the resolution and measurable range of compliance measurement are determined by P/δ. For example, an ultrasound phased array [2] generates about 1.6 gf at a point of 1cm diameter on a surface 20cm away from the array. If one uses the displacement sensor of 0.2 μm accuracy as an experiment in next chapter, the resolution of the spring constant k is about 80 kN/m. Then, we show what parameter of elasticity is corresponding to the value. Displacement u caused by uniform distributed pressure P on a circular area in the surface of an isotropic elastic half-space is theoretically expressed as

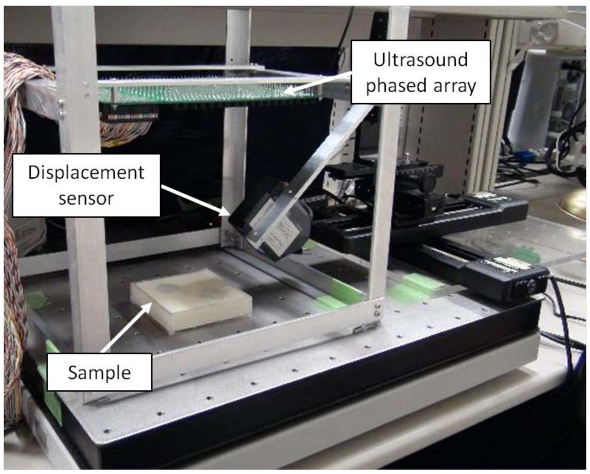
$$u = \frac{(1-\sigma)Pa}{2G} \tag{3}$$

where a is a force distribution radius, σ and G are a Poisson's ratio and a shear modulus of the elastic half-space, respectively. Assuming that the elastic body is soft rubber ($\sigma \approx 0.49$, $G \approx 0.5\mathrm{MPa}$), the spring constant $k = P\pi a^2 / u$ is nearly equal to 31kN/m. Actually, this value becomes smaller because of an finite elastic body.

The spatial measurable range is determined by the aperture of the ultrasound phased array. The spatial resolution of measured compliance distribution is determined by a focal point positioning resolution of the ultrasound phased array. The focal point positioning resolution depends on the ultrasound phased array system and it is 0.5 mm in [2].



(a)



(b)

Figure 2. (a) Experimental setup. (b) Picture of experimental setup

The frame rate limitation f_{samp} of scanning the focal point of the ultrasound beam is expressed as

$$f_{samp} = 1 / (n_{samp} \cdot t_{update}) \quad (4)$$

where n_{samp} is the number of sample points on the surface, and t_{update} is an updating time of the focal point. For instance, $t_{update} = 0.25$ms in [2], $f_{samp} = 1.3$Hz at $n_{samp} = 1000$.

4 EXPERIMENT

We performed three experiments to confirm feasibility of the principle. The first experiment shows that proposed method obtains proper compliance values corresponding to samples which have different hardness from each other. The second experiment shows a possibility of measuring compliance from sinusoidal response of displacement. The last experiment shows that this system acquires a proper surface compliance distribution for a sample which has a characteristic surface compliance distribution.

4.1 Experimental Setup

The proposed system measure a surface compliance distribution of a fixed object by a fixed ultrasound phased array and a laser displacement sensor attached to automatically driven XY-axis stage as shown in Figure 2(a) and (b). In this paper, the ultrasound phased array is identical to a tactile display device used in [2] as shown in Figure 3. An ultrasound beam from the phased array is focused on arbitrary point in a space, and the focused ultrasound generates large acoustic radiation pressure. Thus, by controlling the phased array, it enables us to apply the pressure on arbitrary point on a remote object surface.

Figure 3. Ultrasound phased array which employed in experiment.

The ultrasound phased array has 324 transducers arranged on lattice points of square grid of which span is 10mm. The size of the aperture is 20 cm by 20 cm and thus it can focus the ultrasound beam at a point about 20cm away from the phased array. Each transducer radiates 40 kHz frequency ultrasound and the wave length is approximately 8.5mm in atmosphere at normal temperature. Since the diameter of the focal point is comparable to the wave length, the diameter is also about 8.5mm. The other performance of the ultrasound phased array as follows:

- The output spatial range of the focal point is about 40cm height from the phased array and about 20cm×20cm wide.
- The typical force generated by the phased array is examined as about 1.6gf by an actual survey, and the magnitude of the force is approximately constant in a plane parallel to the phased array.
- The spatial resolution of the focal point is about 0.5 mm.

Displacement caused by ultrasound acoustic radiation pressure was measured using a laser displacement sensor (Keyence Corp. LK-G80). The sensor was attached to an automatically driven XY-axis stage and followed the scanned ultrasound focal point by the ultrasound phased array. To prevent the sensor from obstructing propagation of ultrasound, it measured the displacement from 45 degrees angle against normal direction of the surface. If the displacement was very large and the neighbor area was not displaced, the neighbor area would obstacle the incident or reflecting laser beam of triangulation. But the displacement does not get large like that because of sufficient weak acoustic radiation pressure.

In performed three experiments, we evaluated some samples of urethane gel (Exseal Corp.) as shown in Figure 4. The gel samples were filled into acrylic containers (50mm × 50mm × 20mm). In the first experiment, five samples shown in Table 1 were used. We measured the displacement caused by ultrasound acoustic pressure at the center point of the surface for each sample. Because each sample has different hardness, it enables to confirm sensitivity of this system. It is expected that the smaller displacement is obtained when the sample is harder. In the second experiment, we measure sinusoidal response of displacement at the surface center points on the two samples which have different hardness. The response was obtained by applying ultrasound beam modulated 1Hz rectangular pulse for 10s. In the last

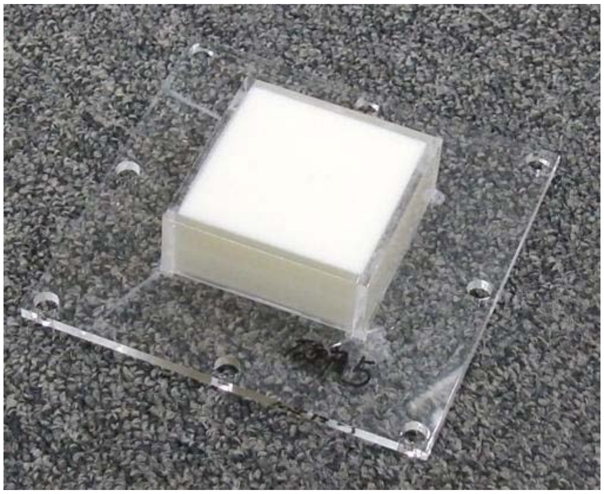


Figure 4. Urethane gel sample of hardness 5 (Asker C) in a container.

Table 1. Samples for the first and the second experiments of non-contact compliance measurement

Sample	Hardness (Asker C)	Notes
A	0	
B	2.5	A mixture of gel of hardness 0 and 5 in the ratio of 1:1
C	5	
D	10	A mixture of gel of hardness 5 and 15 in the ratio of 1:1
E	15	

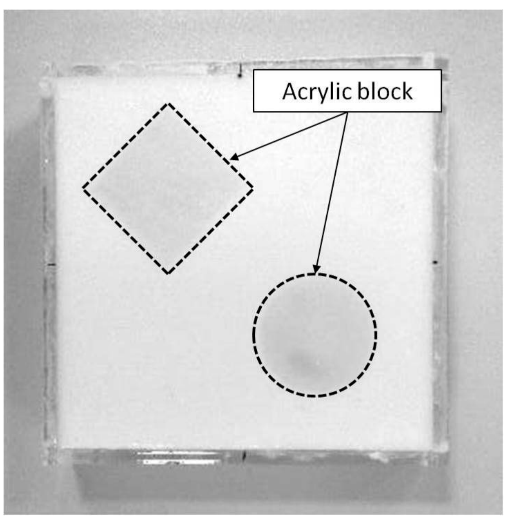


Figure 5. Top view of sample including acrylic blocks.

experiment, we measured the surface compliance distribution of a sample of urethane gel in which acrylic blocks was embedded as shown in Figure 5. This sample fills the 100mm × 100mm × 20 mm container which was glued to a square and a circle section acrylic block on the base. Because the sample has a flat surface and the acoustic radiation pressure is constant independent of the position of the focal point, the surface compliance distribution is measured as the displacement distribution. Because the

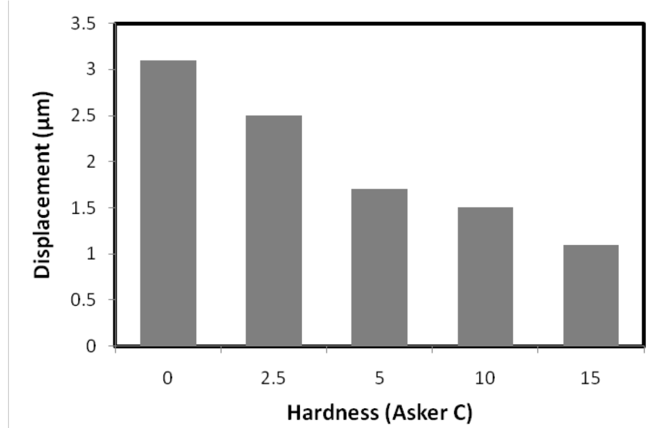


Figure 6. Displacement at a center point of each sample caused by ultrasound acoustic pressure.

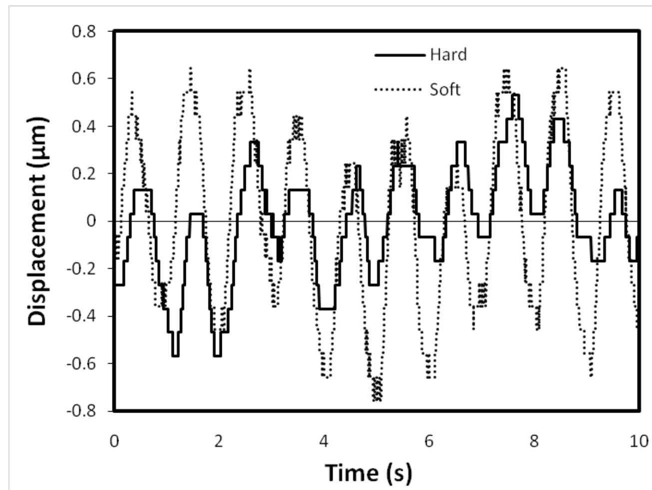


Figure 7. Sinusoidal response of displacement at a center point of two samples.

compliance would be low at the area of existing acrylic blocks, it would be expected that the small displacement would occur there. The surface compliance distribution was acquired by scanning the measuring point. The scan was carried out at 3mm step and the range is square of 90mm by 90mm.

In Figure 2(b), the whole system was set on a passive vibration isolation system because displacement generated by ultrasound acoustic pressure is very small enough to be affect by minute vibration of the ground. The ultrasound phased array was arranged 20cm above the sample and radiated ultrasound to downward. The laser displacement sensor was fixed to the automatically driven XY-axis stage by an aluminum frame. At the first of the experiment, we adjusted the coordinate's origins of the phased array and the automatically driven XY-axis stage. The surface compliance at a point was measured by recording displacement as the difference of the height before and after force exerting on the surface.

4.2 Results and Discussion

The result of the first experiment is represented in Figure 6. It is observed that the surface displacement is monotonically decreasing as the hardness increases. This result shows that the surface compliance distribution can be measured in the range of Asker C hardness from 0 to 15 at least. And the surface

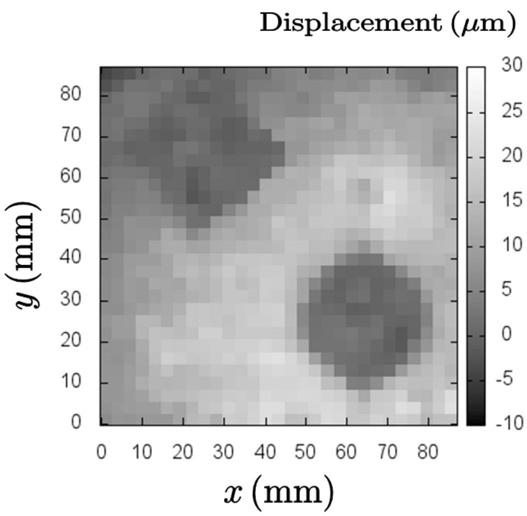


Figure 8. Result of surface displacement distribution of the sample.

displacement acquired in this system is partly associated with the industrial representation of hardness (Asker C). Complete quantification of compliance measured in this system is a future work. The result of the second experiment is shown in Figure 7. The vibration amplitude of a harder sample is smaller than that of a softer sample. According to the result, the proposed system can also acquire compliance by measuring amplitude. Moreover, it means that the system has a potential for measuring parameters of a dynamical system such as viscosity. The measured displacement distribution in the last experiment is shown in Figure 8 for the measured sample shown in Figure 5. In Figure 8, the grey values indicate the displacement and the lighter color shows the larger displacement. The displacement is proportional to the compliance since the exerted force on the surface is constant. In Figure 8, domains corresponding to the areas where acrylic blocks exist in Figure 5, which are the upper left square and the lower right circle, have darker color. Because the darker color indicates that the area is harder than the other area, we can say that the proper surface compliance distribution was measured by the proposed system.

The time for the measurement in the last experiment was about 45 minute. The measurement time in every point is about 3s, and moving the displacement sensor by the mechanical XY-axis stage occupied most of that time.

5 Conclusion

In this paper, we proposed a remote measurement system of surface compliance distribution for haptic broadcasting. Our system consists of an ultrasound phased array generating acoustic radiation pressure and a laser displacement sensor. The compliance is evaluated by the ratio of the surface displacement to the applied force. We set up a system to examine the feasibility of the method. In the experiments, the distribution of the surface compliance comparable to the human skin was successfully measured for a flat object surface. The future works are to cope with a free curved surface and to shorten the measurement time.

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