Touch sense control of an air pillow driven by a piston-cylinder mechanism

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Abstract— **We propose a design and control of an air pillow system (IAAP: Impedance Adjustable Air Pillow), in which users can independently adjust its height and tactile sensation. The IAAP consists of an air bag with a pressure sensor and a motor-driven piston-cylinder mechanism. Because the IAAP does not contain any mechanical sensors inside the air bag, by using only the air pressure and the piston position, we propose an impedance control method to set the target impedance (rigidity and viscosity) of the air bag. To evaluate the usability of our IAAP, some sensory evaluation tests were carried out on a group of subjects. As a result of the tests, we conclude the IAAP has a good practical potential as a high-performance pillow for comfortable sleep.**

Keywords-component; Pillow; Touch sense; Actuator; Impedance control

I. INTRODUCTION

As an increasing number of people around the world become health conscious, research and development of high-performance pillows that enable more comfortable sleep has advanced. Numerous factors determine the comfort of a pillow including basic structural attributes such as height, size, and weight; tactile attributes such as hardness, rebound, and haptic sensation; and even features such as cover design, color, and fragrance. Of these attributes, the pillow's height and tactile sensation (rigidity, viscosity, and inertia) are the most important in ergonomic terms. It is particularly important to be able to independently set the height and hardness (rigidity) to suit the user's preference.

To meet these needs, a variety of products have been developed and marketed, ranging from high- to low-rebound pillows consisting of materials such as polyester, buckwheat husk, pipe beads, water, air, urethane, and feathers. Because these pillows are fabricated by a passive process of filling them with their respective filling materials, their height and hardness are predetermined and cannot be modified to suit individual user preferences. Therefore, research has begun on processes that allow pillow height and rigidity to be actively controlled with the use of actuators. One such pillow, into which vertically activated solenoid actuators are installed directly, has been proposed in previous research [1].

This method, however, entails increased weight of the pillow portion that comes into direct tactile contact with the user. In addition, the mechanical noise generated inside the pillow, immediately in the vicinity of the user's ear, is a major problem (Issue 1).

On the other hand, a method for controlling height and hardness by adjusting the air pressure within an air pillow has also been proposed [2]. This method, however, poses the problem that a simple increase in air pressure increases not only height but also rigidity; that is, this method does not allow for the independent configuration of these attributes, and this method does not allow for viscosity to be adjusted (Issue 2).

The aim of this research is to devise and verify a method for overcoming both Issues 1 and 2.We propose, design, and then verify in experiment an air pillow system (IAAP: Impedance Adjustable Air Pillow), consisting of an air bag with an air pressure adjustment function achieved by active impedance control. This air pillow is lightweight and quiet, and allows users to control height and tactile sensation (rigidity and viscosity) independently.

In Section 2, we present an overview of the IAAP hardware and its linearized dynamics. In Section 3, we describe the characteristics of the IAAP control system, two control methods that are derived from these characteristics, and the experimental results. In Section 4, we report and discuss the results of evaluations carried out on subjects. Our conclusions are presented in Section 5.

II. IMPEDANCE ADJUSTABLE AIR PILLOW HARDWARE

A. *Impedance Adjustable Air Pillow overview and structural characteristics*

An overview of our IAAP is shown in Figure 1. The piston is driven by a DC motor, whose position is measured by a potentiometer, and the air pressure in the air pillow is measured by an air pressure sensor. A pipe connects the air bag to the cylinder, and the goal is to configure the pillow's height and impedance independently by actively adjusting air pressure inside the air bag. The reasons for employing this hardware configuration are listed below.

- The drive mechanism is simple, small, and lightweight.

Instead of using a compressor that is typically heavy and large, IAAP consists of a simple, small, and lightweight construction whereby the air bag is connected via a pipe to a motor-driven piston cylinder mechanism.

- The pillow is quiet, safe, and lightweight.

Owing to the use of the long pipe, the drive mechanism and bag can be kept separate, thereby making the portion that comes into human contact quiet, safe, and lightweight.

- Customization of the bag is simple.

Low-cost vinyl fabrication allows for easy modification of the airbag shape and rigidity to suit user preferences.

These features are advantageous over conventional systems that use actuators directly inserted into the pillow or a compressor. This configuration, unfortunately, is not without its disadvantages. The IAAP does not contain any mechanical sensors inside the air bag, as these might be perceived as a foreign object by users; consequently, the height of the air bag cannot be measured directly.

This problem represents the primary technological challenge with regard to the design of an IAAP control system.

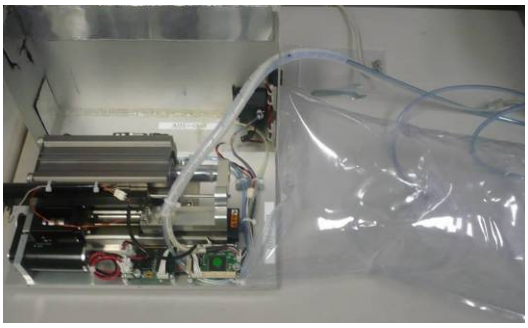

Figure 1. The piston-cylinder air pressure control system

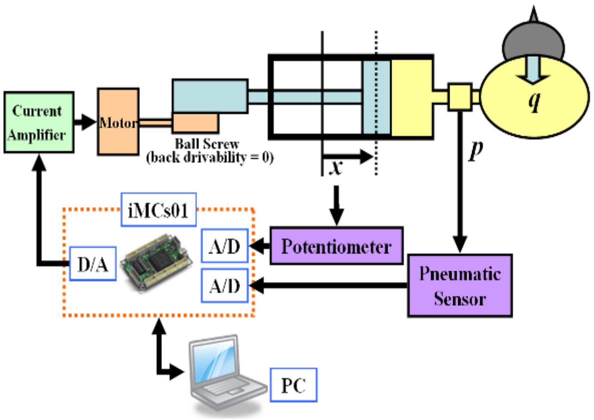

Figure 2. A physical model

B. *Linearized dynamics of Impedance Adjustable Air Pillow*

Figure 2 shows a physical model of the pillow on which a human head rests. Here, q is the force that the head exerts on the pillow, h is the pillow height, x is the piston position, and p is the air pressure in the air bag. The conditions of this system that enable controllability from u, as well as observability from p, are described in the following sections.

III. IMPEDANCE ADJUSTABLE AIR PILLOW IMPEDANCE CONTROL SYSTEM

A. *Underlying concept*

The technological challenge that we aim to overcome in this research is the ability to independently configure height and tactile sensation (rigidity and viscosity). In other words, the following characteristics must be achieved:

$$m\ddot{h} + d\dot{h} + k(h - h_{ref}) = q \cdots (1)$$

Here, h_{ref} is the target height of the pillow, and k, d, and m are the impedance parameters of rigidity, viscosity, and mass, respectively. Satisfying Equation (1) is simple if h and q can be directly measured. Specifically, one could first design a broadband positional control system for h, and then generate h_{ref} as described below based on q and the target impedance parameter. However, because of this system's structural advantages described in 2.1, direct measurement of h and q is not possible. Therefore, we focus on how Equation (1) can be satisfied using x and p both of which are directly observable. In cases where the parameters of Equation (2) are known and unvarying, the linear observer allows for h and q to be estimated from x and p. Unfortunately, such an observer is practically difficult to realize, because the airbag film (vinyl) exhibits nonlinear and distributed constant physical characteristics that are susceptible to variations caused by external factors such as temperature. Moreover, if we assume that the shape and size of the airbag are varied to suit user preferences, it would not be realistic to identify the controlled object in each instance.

Therefore, this method requires a degree of engineering compromise to satisfy the conditions of Equation (1). Based on these considerations, in the following section, we propose control methods based on an open loop construction that can be realized with the use of only x and p.

B. Method 1

From the perspective of pillow use in real-world situations, users often find it difficult to explicitly describe the preferred height and tactile sensation of their pillows, and there is little point in precisely expressing these characteristics numerically. A more realistic scenario would be one in which the user is given the ability to manually control these attributes while his or her head is actually resting on the pillow. Therefore, because the approximation $q \propto p$, $h \propto x$ can be established in a static state, the following is proposed as a simplified form of Equation (2), which is derived by substituting p for q and x for h:

$$d\dot{x} + k(x - x_{ref}) = p \cdots (2)$$

If the control bandwidth with respect to the piston position is sufficiently broad, and $x=x_{ref}$ can be established within a practical range, the impedance parameters achieved at the tip of the pillow are as follows. This means that the following equation can be used to achieve the preferred rigidity and viscosity by making adjustments to k and d. Results of experiments conducted based on this method are shown in Figure 3. Figure 3 shows that the desired characteristics are obtainable within ranges where there is no substantial variation in piston displacement. However, passive compliance of the air pillow is a function of air pressure and is therefore not a constant. Therefore, when substantial piston displacement occurs, the set compliance value deviates from the set value as shown in Figure 3.

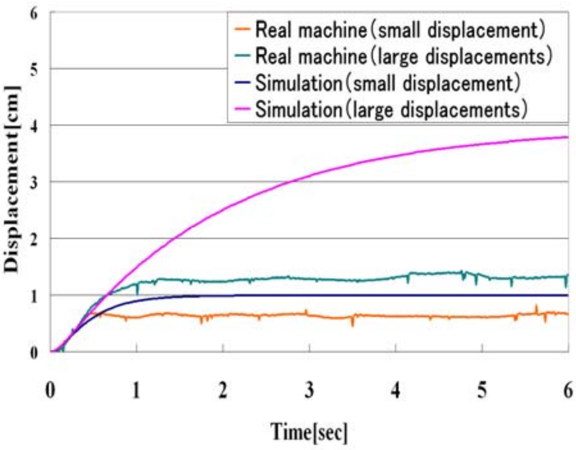

Figure 3. The piston-cylinder air pressure control system

C. Method 2

While q is directly proportional to p in cases where the piston position remains unchanged, this relation does not hold if the piston position changes because the air spring value depends on air pressure. Here, q is estimated from p and x by applying Boyle's law and Pascal's principle, and this q' (estimated q) is used to solve the fault in Equation (1).

The system comprising the air pillow and piston can be rendered into an approximation model as shown in Figure 4. Here, P_0 is initial air pressure. V_0 is an initial volume of air cushion and piston. P_a is air pressure value after the change. S_h is an area of the contacts with a pillow. S_P is an area of the cylinders. x is displacement of the pistons. h is displacement of the pillow height. k_b is an equivalent spring constant by the air pillows cuticle hardness. and The external force that F estimates it.

Equation (3) is obtained by applying Boyle's law and Pascal's principle to this model. In other words, it can be expected that external forces can be estimated based on air pressure and piston position information for quasi-static situations as in Equation (4). This method for estimating external force is verified in the following section.

$$\left.\begin{aligned} P_0 S_h &= f_0 + S_h \\ P_0 V_0 &= P_a V = P_a (V_0 - S_h h + S_p x) \\ P_a S_h &= f_0 - k_b h + F + S_h \end{aligned}\right\} \cdots (3)$$

$$F = (P_a - P_0) S_h + \frac{k_b P_0}{S_h} x - \frac{k_b P_0 V_0}{S_h P_a} + \frac{k_b V_0}{S_h} \cdots (4)$$

1) Validating external force estimation method

Figure 5 shows results of a measurement experiment that was carried out to validate the proposed method for external force estimation. A 9.8 N weight was placed on the upper portion of the pillow and was moved slowly by a piston. The figure shows the difference between estimates made using the proposed method and a method using only an air pressure sensor with no corrections for piston position. It can be seen in Fig. 5 that while external force values estimated with the use of air pressure alone decrease significantly as the piston moves, values obtained by the proposed method, although they vary slightly from initial estimates, are closer to the initial pressure in a quasi-static state. This confirms that the precision of external force estimation using the proposed method is considerably better than the method using air pressure alone.

2) Controlling impedance using a mechanism for estimating external force

Since the preliminary experiment mentioned above confirms that quasi-static estimations of external forces are possible, we now propose a method for controlling impedance using external force estimation. Impedance control formulation is expressed in Equation (5). Here, k_d, d_d, and m_d are the impedance parameters of rigidity, viscosity, and mass, respectively. Figure 6 shows a control block diagram.

$$X_r = \frac{F + k_d X_d}{m_d S^2 + d_d S + k_d} \cdots (5)$$

$$F = (P_a - P_0) S_h + \frac{k_b P_0}{S_h} x - \frac{k_b P_0 V_0}{S_h P_a} + \frac{k_b V_0}{S_h}$$

3) Stand-alone experiment

A constant load (20 N) was applied to the upper portion of the air bag as a step input, and the displacement of the top of the bag was measured to examine the nonlinearity of the air bag. Figure 7 shows the results of measurements taken for different spring components, viscosities, and mass values at the target impedance shown in Equation (3). Figure 8 shows the results of measurements taken when rigidity is fixed and the height of the bag is varied.

a) Case of constant initial height

Figure 7 shows that the steady-state value of displacement varies when changes were made to the specified impedance value. Therefore, this allowed us to verify the effects of changing impedance values.

b) Case of fixed rigidity and varied initial height

Both graphs show generally parallel upward and downward movements as shown in Figure 8; thus, we are able to confirm that height and rigidity are being controlled independently. We also verified that the passive rigidity inherent to the airbags varies considerably depending on the shape of the airbag and its internal pressure. These findings are shown in the encircled area in Figure 8.

For comparison, Figure 9 shows data obtained for the method of impedance control based on estimation of external force using only an air sensor with no information regarding piston position. These results demonstrate the validity of the proposed method.

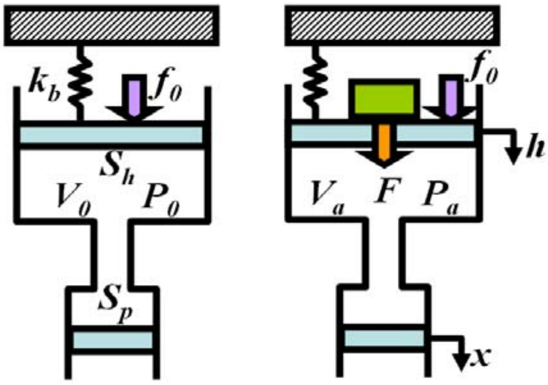

Figure 4. An approximation model

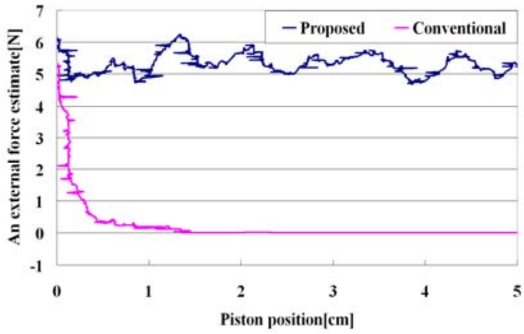

Figure 5. The comparison of the external force estimate method

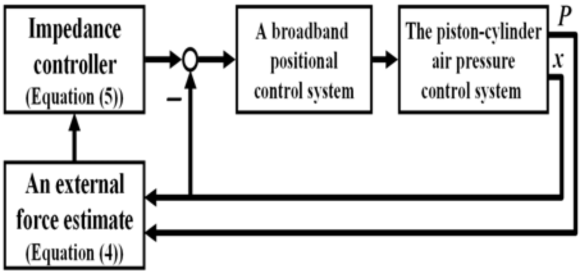

Figure 6. A control block diagram

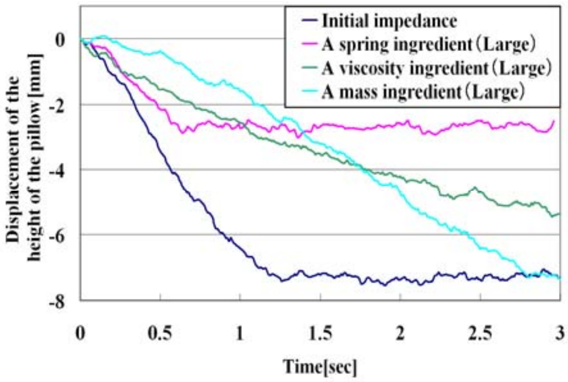

Figure 7. The change result of the impedance parameter

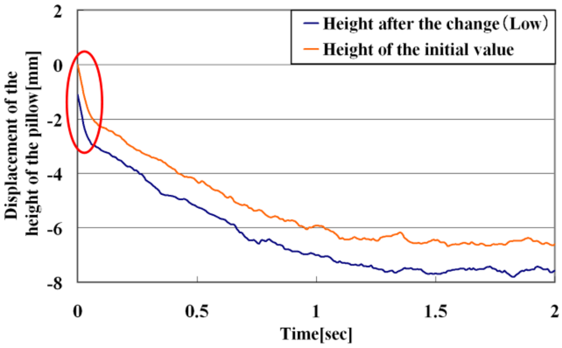

Figure 8. The height change result

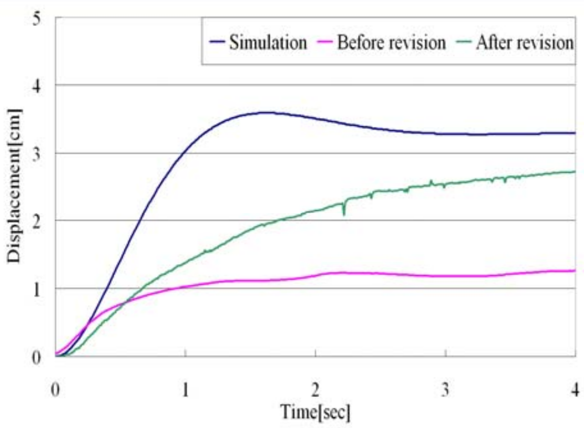

Figure 9. A comparison result of the external force estimate technique

IV. EVALUATION TESTS

To evaluate the usability of the IAAP system, two types of sensory evaluation tests were carried out on a group of subjects. The group consisted of 14 healthy students who were approximately 20 years old, all of whom were information sciences majors. The subjects were asked to evaluate the sensations felt on their heads as they lay down on a bed and rested their heads on a variety of pillows, as shown in Figure 10.

A. *Experiment*

Objective and overview: The objective of this experiment was to verify whether or not human senses pertaining to the head are able to sense and discern variations in impedance parameters produced by IAAP. Two comparison objects (4 versions) in terms of rigidity and viscosity were used and tests were carried out to determine to what degree these variations could be sensed by the subjects. The four patterns show Table 1. Initial pillow heights were all set to the same height.

Procedures:

(1) Subjects are given an explanation of the meaning of rigidity and viscosity in physical terms.

(2) Subjects are asked to use Patterns 1 and 2 for 1 minute each, and asked to identify which of the versions exhibited greater rigidity.

(3) Subjects are asked to use Patterns 3 and 4 for 1 minute each, and asked to identify which of the versions exhibited greater viscosity.

(4) After the experiment, subjects are interviewed on how the pillows felt.

1) *Results*

The rate of correct answers given is shown in Table 2.

2) *Evaluation and discussion*

Table 2 shows that variations in rigidity and viscosity produced by the stand-alone use of the IAAP are clearly perceived by the subjects.

The percentage of correct answer of the viscosity is lower than that of the stiffness. One of the reasons is that the cylinder capacity of the system is too small. Because the viscous term is proportional to speed, it is important whether or not the height change rate of the air pillow can be perceived by the head of the subject. Consequently, for the longer time the piston moves, the clearer the subject can feel the rate. Unfortunately, the piston cannot continue to move one way for long time since the piston's range of the movement is too small. Therefore, we can interpret that the piston moved to it's limit before the subject could notice the speed change. As a comprehensive result, since the majority of the subjects could percept both the stiffness and the viscosity, we can conclude that the proposed system has an ability to express the change of the stiffness and the viscosity for users.

The following are some of the impressions most cited by subjects at the interview:

"I was not clear on the difference between rigidity and viscosity at first, but I began to notice a difference after I moved my head around a number of times."

"Compared to the rigidity, the difference of the viscosity was difficult to sense."

"The sense of touch changes depends on the position of the head on the pillow because the pillow is too small. "

"The subduction is difficult to recognize because the pillow is small."

"Changes of these parameter can only be recognized as errors of sense."

The system has good practical potential from the perspective of user satisfaction in day-to-day use.

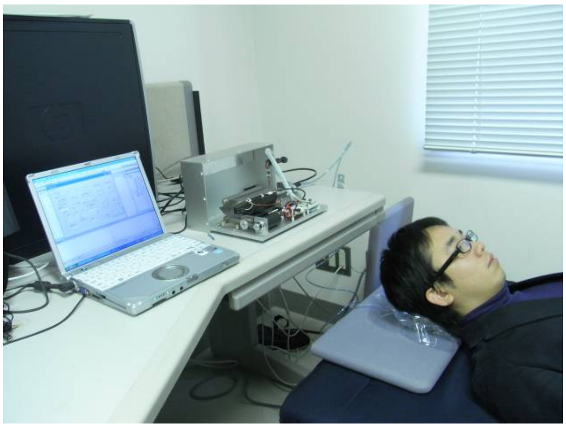

Figure 10. The comparison of the external force estimate method

TABLE I. THE FOUR PATTERNS

		Stiffness	
		Large	*Small*
Viscosity	*Large*		Patterns 3
	Small	Patterns 1	Patterns 2 Patterns 4

TABLE II. THE RATE OF CORRECT ANSWERS

	The rate of correct answers
Stiffness	100%
Viscosity	71%

V. CONCLUSION

We proposed a design and control of the IAAP in which users can independently adjust its height and tactile sensation. The IAAP consists of an air bag with a pressure sensor and a motor-driven piston-cylinder mechanism. An impedance control method has been proposed by using only air pressure and the piston position. For validation, some primary experimental results have been provided as well as some sensory evaluation tests for the usability of the IAAP on a group of subjects. As our future work, we will execute more sensory evaluation tests including comparisons between the IAAP and store-bought pillows.

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