

Impulsive resistance force generated using pulsive damping brake of DC motor

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Abstract—We developed a method to present an impulsive resistance force by using the passive damping brake of a DC motor. The rapid pulsive change in the resistance forces preceding the main brake increased the perceived resistance of the brake. In a ranking task involving five naive participants, a damping brake with two preceding pulsive resistances was reported to deliver a resistance larger than that due to a simple stepwise brake that achieves the maximum physical braking force. This finding indicates that perceptually effective impulsive resistances are different from the physically optimal resistance. Our technique enhances the abilities of passive force displays, which are inherently safe human-machine interfaces.

I. INTRODUCTION

Passive haptic interfaces, which take advantage of mechanically or electrically passive elements to present haptic stimuli, are beneficial for industrial and entertainment applications because of their inherent safety and energy efficiency. Several researchers have employed passive haptic interfaces for force and tactile texture displays [1], [2], [3], [4] and human-machine coexistence systems [5]. The origin of such passive interfaces can be seen in passive robotics [6]. The present study deals with impulsive resistance forces generated using only a passive damping brake. Representation of impulsive resistance forces to the users of teleoperation robots or virtual reality systems allows them to feel the hard contact with virtual objects. For delivering a sense of hard contact, providing a large momentum with the hand of the maneuverer in a short period is effective [7]. However, passive force displays can only deprive the maneuverer of momentum. Therefore, for a passive interface, it is believed that braking with the maximum resistance is the best method to present a large resistance.

The objective of this study is to present a large impulsive resistance force by using the passive damping brake of a DC motor. We aimed at a resistive force pattern that induces a greater resistance than that perceived by the physically maximum damping torque of the DC motor. Regarding the loss of momentum of the moving hand of the maneuverer, the maximum physical resistance force is achieved by the continuous function of the damping brake. This continuous brake at the maximum braking force is also believed to be perceptually most effective to evoke the sense of impulsive resistive force. In contrast, we experimentally confirmed that the pulsive resistance force caused by rapidly switching the damping brake on and off can evoke an even larger resistance perception. To the knowledge of the authors, thus far, few

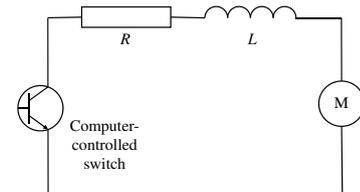


Fig. 1. Computer-controlled short circuit of the DC motor.

researchers have reported such a perceptual effect or method for presenting large impulsive resistances by using only passive force control elements. Furthermore, we investigated the perceptual characteristics of the impulsive resistance forces in order to find a way to optimize the brake-force profiles. Such a technique for impulsive resistances using passive haptic interfaces will benefit the teleoperation robotics and gaming industry, in which safe and stable force displays are preferred.

II. PRINCIPLE

A. Short-circuit-brake of DC motor

We employed the damping brake of a DC motor as a passive factor. This brake functions by shortening the motor circuit and using the back electromotive force of the motor. Figure 1 shows a schematic of a short circuit in which R and L are the resistance and inductance of the circuit, respectively. When the DC motor rotates at an angular velocity of $\omega(t)$, on the basis of Kirchhoff's law, the brake torque $\tau(t)$ is determined as follows:

$$\frac{L}{R} \frac{d\tau(t)}{dt} + \tau(t) = -\frac{K^2}{R} \omega(t), \quad (1)$$

where K is the torque constant of the motor. Given that the inductance L is negligible, the brake torque $\tau(t)$ is proportional to the angular velocity $\omega(t)$, indicating that the braking force corresponds to the viscous resistance. Such a brake of a DC motor has been used for haptic interfaces to control their passivity or impedance [3], [8].

B. Damping brakes for impulsive resistance

1) *Physically maximum impulse*: We consider a case where a moving human hand hits a wall of large mass as shown in Fig. 2. The integral value of the impulsive force caused by the hit is related to the difference of the momentum of the hand before and after the impact. Provided that the mass of the hand is constant, the impulse is determined by the hand

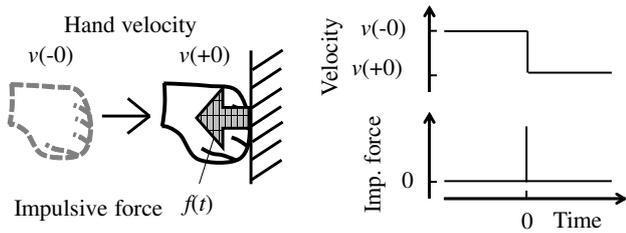
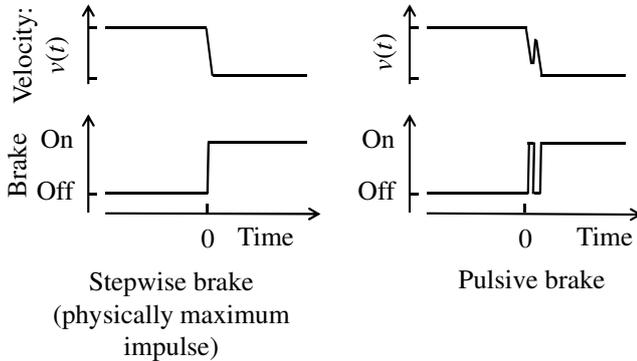


Fig. 2. Impact by hitting a wall. Change in hand velocity and associated impulsive force.



Hypothesis

$$\text{Impulsive resistance perceived by stepwise brake} < \text{Impulsive resistance perceived by pulsive brake}$$

Fig. 3. Two types of impulsive resistances. Left: Change of velocity by a stepwise brake. Right: Change of velocity by a pulsive brake. We hypothesize that the impulsive resistance perceived by the right pulsive brake is greater than that perceived by the left stepwise brake.

velocity. The impulsive force $f(t)$ at contact is denoted by

$$m(v(+0) - v(-0)) = \int_{-0}^{+0} f(t)dt \quad (2)$$

where $v(t)$ and m are the hand velocity and mass, respectively. The moment of contact is $t = 0$. As previously mentioned, from this viewpoint, when the change in velocity before and after the impact becomes maximum, the perceived impulsive force is also maximum. The damping brake that achieves this behavior best is

$$\text{braking} = \begin{cases} \text{off} & t < 0 \\ \text{on} & t \geq 0. \end{cases} \quad (3)$$

Passive force displays achieve the most rapid changes of force outputs and velocity by abruptly exerting the maximum brake force where no force is output. From this viewpoint, braking with the maximum damping force seems to be the best method for delivering the largest impulsive resistance.

2) *Hypothesis about impulse perception and pulsive damping brake:* To improve the quality of the force outputs of haptic interfaces with limited maximum force outputs, the rates of the exerted force are occasionally more important than the

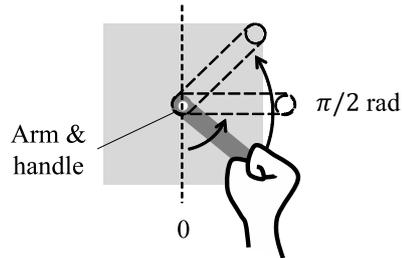
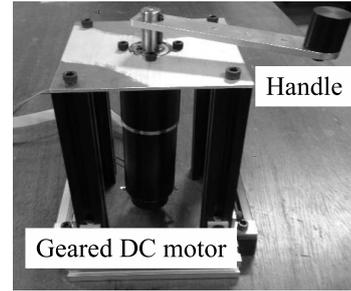


Fig. 4. Top: Passive haptic interface using the damping brake of the DC motor. Bottom: Task to evaluate impulsive resistance forces.

available maximum force. Lawrence et al. [9] demonstrated that it is effective to increase the rate of the force output in order to present the hardness experienced by hitting virtual objects. This indicates that the change in the hand motion or force during a certain short period (Δt) has to be considered explicitly, although in the preceding section the impact was physically modeled as an instantaneous event that occurs over a very short duration: $\Delta t \rightarrow 0$.

We hypothesize that a greater integral value of the absolute change of the momentum in a short period yields a greater perceived resistance. The momentum does not necessarily continuously decrease. Hence, under this hypothesis, the perceived impulse is proportional to

$$\text{Perceived impulse} \propto m \int_0^{\Delta t} |\dot{v}(t)|dt. \quad (4)$$

We switch the brake of the haptic interface on and off, resulting in a large absolute change of the momentum or hand velocity. As shown in Fig. 3, a larger impulsive force may be perceived by an on-and-off brake (right) than by the physically maximum stepwise brake (left). We experimentally validate this hypothesis about human impulsive force perception.

III. EXPERIMENTAL APPARATUS

Figure 4 shows the passive haptic interface based on the damping brake of a DC motor. This device presented the brake force by switching only the short circuit of the DC motor (RE-40, Maxon motor, reduction ratio: 12, inductance: 0.025 mH, torque constant: 16.4 mNm/A). The circuit was controlled by a microcomputer at 10 kHz. The output shaft of the motor was connected to an aluminum arm 120 mm in length with a handle. The rotation angle of the motor was recorded by an encoder mounted on the motor.

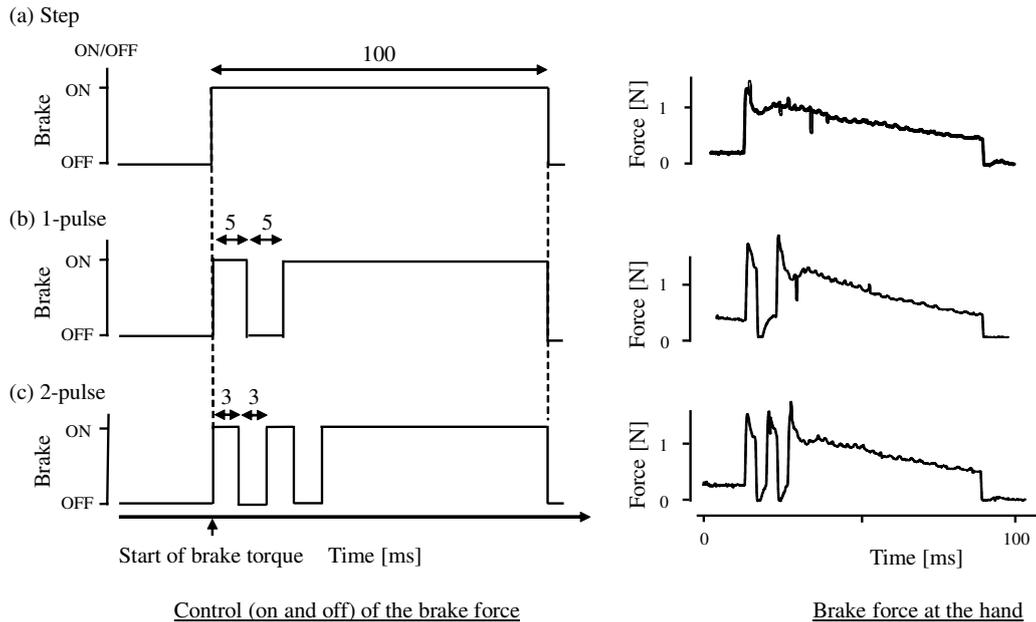


Fig. 5. Three types of braking stimuli. Left: On-off operations of brake torque. Right: Examples of braking forces estimated on the basis of the current.

IV. IMPULSIVE RESISTANCE STIMULI

We investigate whether it is possible to present a perceived resistance larger than that of the stepwise brake. We presented each of the three types of braking forces to experimental participants when they were rotating the arm of the device. The three types of braking forces were stepwise, one-pulse, and two-pulse stimuli. Figure 5 shows the braking operations for each type of stimulus. The stepwise brake was operated at the maximum brake force for 100 ms, which was short and felt like an impact caused by a collision with an object. For the one-pulse stimulus, a pulsive brake of 5 ms preceded the main brake of 90 ms with a 5 ms interval. For the two-pulse stimulus, two pulsive brakes, each lasting 3 ms with an interval of 3 ms, preceded the main brake of 88 ms. The three types of stimuli lasted 100 ms in total.

We regulated the widths and the intervals of the pulses on a trial-and-error basis such that we could perceive the stimuli as realistic impacts. We used one- and two-pulse stimuli, although stimuli with more than three pulses are also possible. A greater number of pulses yields a longer period of continuous pulsive stimuli that are felt as obvious vibrations and deteriorate the realism of the stimuli. Hence, we limited the number of pulses to two; however, these stimuli were experimentally determined, and better stimuli should exist.

V. EXPERIMENT

This study was approved by the internal review board of School of Engineering, Nagoya University (#15-12).

A. Participants

The participants were five volunteer students unaware of the objectives of the experiments. All of them declared that they

used their right hand for writing.

B. Tasks

The participants, whose auditory cues were shutout by headphones playing a pink noise, sat on a chair in front of the device and rotated the arm of the motor with their right hand, as shown in Fig. 4. The braking stimulus was initiated at an angle of $\pi/2$ rad. After experiencing the stimulus, they were allowed to return the arm to the original position (0 rad) and to experience the stimulus repeatedly. They were not instructed on the number of times to test the stimulus, but they typically experienced each stimulus five to ten times. Furthermore, regarding the rotation speed of the handle, they were instructed to use a comfortable speed but not to rotate the arm very fast or slow. The average angular velocities of the handle immediately before the commencement of the stimuli were in the range 5.0-5.9 rad/s for all the participants, and there was no significant difference in the handle speed among the stimuli.

Although the participants were told that there were three types of stimuli, they were not informed of their differences. During the experiment, the participants could freely switch the three types of stimuli by using a keyboard. The correspondence between the keys and stimuli was randomized for each participant.

1) *Ranking task:* The participants ranked the three types of stimuli on the basis of the magnitude of the perceived resistance forces in a forced-choice manner. They were not allowed to rank more than two types of stimuli the same. They conducted the same task after a break of several minutes, so that we could check the consistency of their answers. Nonetheless, no participant ranked the stimuli differently between their

TABLE I
RESULTS OF RANKING TASK

Participants	Ranking		
	Step	One-pulse	Two-pulse
A	2	3	1
B	2	3	1
C	3	2	1
D	2	3	1
E	3	2	1

first and second trials.

2) *Drawing task*: In a preliminary investigation, the people who experienced the stimuli agreed that the resistance force presented by the device was similar to that perceived by contacting and overcoming an obstacle on a plane. Therefore, we asked the participants to draw the profiles of the obstacles associated with each stimulus on a graph paper. They were required to consider the sizes of the obstacles drawn. We expected analyzing the drawings would help us identify the physical factors influencing the perception of impulsive resistance force.

C. Experimental results

1) *Results of the ranking task*: Table 1 presents the results of the ranking task. All the participants reported that the two-pulse stimulus delivered the largest resistance. Following the two-pulse stimulus, the one-pulse and stepwise stimuli were selected by two and three participants, respectively. The ranks of the three types of stimuli differed significantly ($S_0 = 30.8$, $p < 0.05$, Friedman test). In a post-hoc test, we compared all the possible pairs of stimuli by using Wilcoxon's rank sum tests. Differences at a significance level of 0.05 were observed between the stepwise and two-pulse stimuli and between the one-pulse and two-pulse stimuli. These results indicate that the two-pulse stimulus was perceived as a larger resistance than the other two types of stimuli.

2) *Results of drawing task*: Figure 6 shows the profiles of perceived obstacles drawn by the participants. All the participants drew bumpy objects. Participants A, B, and E differentiated the height of the obstacles. For the obstacles drawn by participants A and B, the two-pulse stimulus was the tallest, followed by the stepwise and one-pulse stimuli. Participant E drew the two-pulse stimulus as the tallest and the other two stimuli as equally tall. In contrast, participants C and D differentiated the width of the obstacles, recognizing the one-pulse and stepwise stimuli, respectively, as having smaller widths than the other stimuli. Participants A, C, and D recognized differences in the profiles of the obstacles. Participants C and D expressed the stimuli with pulses as objects with rugged surfaces.

VI. DISCUSSION

In the experiments, a brake stimulus with two preceding pulse stimuli induced the perception of a greater impulsive

resistance. Thus far, few researchers have pointed out that such pulsive damping brakes are perceptually more effective than the stepwise operation for the physically maximum damping brake. The experimental results corroborate our hypothesis on the perception of impulsive resistance forces, which is that the integral value of the absolute velocity change during a short period at the event of impact influences the perceived magnitude of the impulse. Nonetheless, further validation is needed to reach a conclusion. Note that it is unclear that the perceptual effects of the pulse stimuli were attributed to the increase in the absolute velocity change in a short period.

Our hypothetical principle may be related to an increase in the perceived hardness via additional vibratory cutaneous stimuli, though our method is for the impulsive force caused by hitting a hard object. By adding vibratory cueing to the force output of the haptic interface at the event of dynamic contacts such as tapping, the perceived hardness of a virtual object increases [10], [11]. The method employed by these earlier studies and our method are similar in that they increase the perceived hardness or impact by using additional stimuli that do not physically increase the impedance or maximum output forces of the haptic interfaces. However, such vibratory stimuli to the cutaneous channel do not influence the momentum of the hand of the maneuverer. On the other hand, our approach intends to directly manipulate the momentum to represent the impulsive resistance force. Hence, these earlier studies and our present study may underlie different perceptual principles.

One of the next research steps is to specify a brake pattern that leads to the greatest perception of impulsive resistance using a damping brake. However, one concern is the individuality of perception. On the basis of the results of the drawing task, the effect of the pulse stimuli on the perception may have varied among individuals. For some participants, the pulsive stimuli yielded a perception of higher or wider obstacles. For other participants, the pulsive stimuli influenced the profiles of the obstacles. In the future, additional studies involving a large group of participants may make the results of the drawing task more conclusive. Moreover, investigating the relationships between the characteristics of the perceived obstacles and the parameters of braking stimuli, such as the number of pulses, the width, and the interval may provide us with guidelines for designing optimal resistance forces.

VII. CONCLUSION

This study addressed the perception of a large impulsive resistance by using a passive haptic interface with the damping brake of a DC motor. We compared three types of braking stimuli. One was a stepwise brake that exerted a physically maximum brake torque. The other two involved pulsive brake forces before the main brake. Each stimulus included one and two short transient brakes. The perceived resistance forces resembled those experienced when contacting and overcoming an obstacle. When ranking these three types of brakes, study participants judged the two-pulse-typed brake as the largest resistance. This study is the first report that there exists a

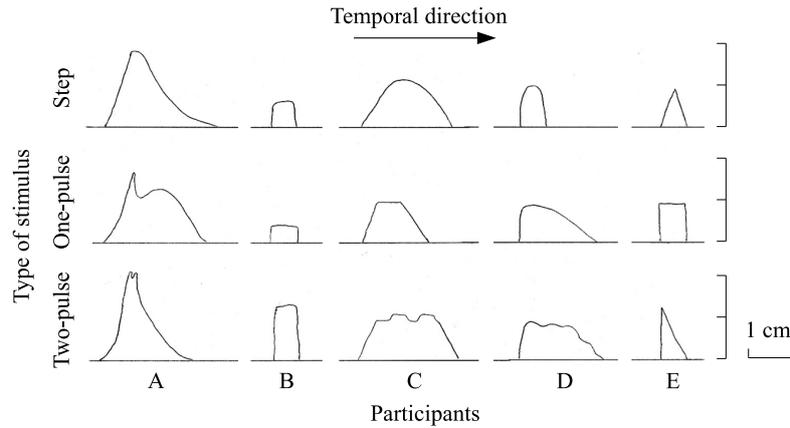


Fig. 6. Drawings of imaginary obstacles perceived by participants.

damping brake operation that yields a greater sense of impulsive resistance force than the physically maximum damping brake. Our finding about the human perceptual characteristics for impulsive resistance will further exploit passive haptic interfaces which are compatible with many industrial applications because of their inherent safety.

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