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Passive-type Rehabilitation Systems for Upper Limbs with MR Fluid Brake and Its Training Software

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Abstract— **It is important to construct rehabilitation system for elderly people, people who have suffered strokes, and so on. In recent years, the need for rehabilitation support systems is increasing that using force display devices. When using force display systems, it is most important to ensure safety mechanically in order to prevent operators from hurting. Conventional force display systems are active-type devices with actuators but these devices may become dangerous when going out of control. On the other hand, passive-type force display devices with only passive elements are thought to be an effective method for assuring inherent safety. In this paper, we evaluate force display ability about a 2-D passive-type force display device with fast-response MR (Magneto-Rheological) fluid brakes to apply this device to rehabilitation training.**

I. INTRODUCTION

In these days, the number of people with motor disorders caused by cerebral apoplexy will increase. Current society is faced with the task of creating rehabilitation centers for these people. Upper limb disorders are more difficult recover from than lower limb disorders. The recovery of upper limb function is strongly correlated with ADL (Activities of Daily Living). Rehabilitation for upper limb disorders is therefore important. Force display systems may be used for upper limb rehabilitation support.

Force display systems are classified into two types: active type and passive type. Active type systems use an actuator such as a motor to generate force. Passive type systems, in contrast, use component such as brakes.

Attention must be given to safety when using force display systems for rehabilitation. With the active type system, accidents may occur due to system errors and improper use. Passive type systems are, in contrast, safe because handles or arms are always passive. Even if control systems or digital circuits malfunction, no harmful force is applied to the user. Passive type systems can therefore be used to display large amounts of force. Passive type systems can, furthermore, be made compact and inexpensive.

Passive type systems developed so far use electromagnetic friction brakes, particle clutches, and functional fluid brakes. Electromagnetic friction brakes have poor control and response. Particle brakes have a time constant of about 50-100 milliseconds and have poor response as well as electromagnetic friction brakes.

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Functional fluid brakes, in contrast, have good response speed. These brakes are suitable for upper limb rehabilitation support systems. The two major types of fluid for functional fluid brakes are ER (Electro-rheological) and MR (Magneto-rheological) fluid. The viscosity of ER fluid changes when an electric field is applied. The viscosity of MR fluid changes when an magnetic field is applied. The time constant of MR and ER fluid is a few ms. In research led by Furusho, a passive type system was created with an ER fluid brake and an active type system was created with an ER fluid actuator [1]. Moreover, an actuator with MR fluid being created, active type force display device was developed.

Reed and Book of Georgia University developed a passive type force display system, MR P-TER, which uses MR fluid brakes [2]. The system uses a commercial MR fluid brake (Lord's MRB-2109-3), however. This fluid brake has poor response due to backlash.

In our research, we used a fast response MR fluid brake in a 2-D passive type force display system. The system was used for rehabilitation training of the upper limb. The MR fluid brake that we used has low output torque and a low moment of inertia. It was also designed to reduce eddy current [3]. This MR fluid brake therefore has a fast response time. "MR-PLEMO" will be introduced in this paper. "MR-PLEMO" is a passive type system that uses fast response MR fluid brakes. We will also perform basic experiments; vibration display, wall surface display, and viscous resistance display. The developed system will be used in a rehabilitation program for upper limbs.

II. REHABILITATION SUPPORT SYSTEMS FOR UPPER LIMBS THAT USE MR FLUID BRAKES

A. Rehabilitation Devices for Upper Limbs that use Functional Fluid Brakes

So far, we have been developing force display systems that use brakes. These systems are the PLEMO-Series (PLEMO-P-Prototype, PLEMO-P1, PLEMO-P2, PLEMO-P3, PLEMO-P4, PLEMO-P5, PLEMO-Y). The system that we first developed is the 2-D force display device PLEMO-P-Prototype (Virtual Reality Society of Japan Paper Award Winner) [1] . Based on this system, we developed quasi-3D rehabilitation support systems, PLEMO-P1 and PLEMO-P2 (joint research with Hyogo College of Medicine). And we conducted practical application, developed PLEMO-P3 and PLEMO-P4. On PLEMO-P3 and PLEMO-P4, several tests with hemiplegic subjects were performed to evaluate the effectiveness of these systems[4]. PLEMO-Y was developed toward a practical use with support from the project of

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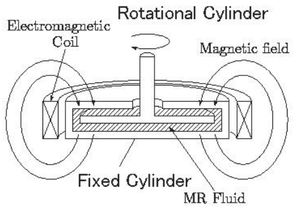

Fig. 1. Conceptual illustration of MR fluid brake

Fig. 2. Overview of a developed fast-response MR fluid brake

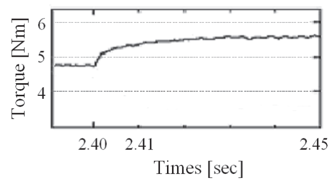

Fig. 3. Response data of the fast-response MR fluid brake

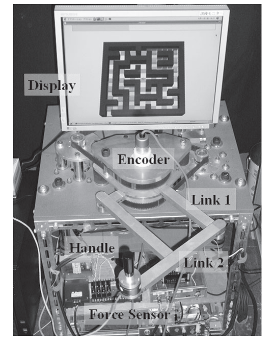

Fig. 4. Overview of 2-D passive force display system "MR-PLEMO"

Ministry of Economy, Trade and Industry in 2011. Now, we are improving PLEMO-Y to place this system on the market in fiscal 2013.

We have developed a new rehabilitation support system for upper limbs, "MR-PLEMO." The above PLEMO-Series uses ER fluid brakes, but MR-PLEMO uses MR fluid brakes. MR and ER fluid brakes both have high responsiveness. Conventional ER fluid brakes require high voltage (few kV) and low current (few mA). Conventional MR fluid brakes, in contrast, require low voltage (few V) and high current (few A). There is not much difference in energy consumption between the two fluids. MR fluid brakes can however generate large torque and do not require a high-voltage power source. MR fluid brakes are therefore more suitable for compact systems.

B. Fast Response MR Fluid Brake

Application of magnetic fields to MR fluid (Magneto-Rheological fluid) changes its rheological property. MR fluid is a noncolloidal solution. A few μm orders of magnetic metallic particles are mixed into an oil-based dispersion medium. MR fluid generates 50-100 kPa of shearing stress. The response speed is also fast. MR fluid can be used to create brakes with high torque and high responsiveness.

The basic structure of the MR fluid brake is shown in Fig.1. MR fluid fills the space between the fixed cylinder and rotating cylinder. When an outside magnetic field is applied, the apparent viscosity of MR fluid changes. This viscosity change is converted to torque of the brake. Torque is then transferred to the output axis.

The MR brake that we developed is shown in Fig.2. The diameter of this brake is 170 mm, and the maximum torque is about 10 Nm. We performed an experiment to check this brake's step response. In the experiment, current was changed from 0.4 to 0.5 A. Measurements from the experiment are shown in Fig.3. Results show good responsiveness.

Figure 3 shows two stages of the MR brake step response. Note that an initial rise is followed by a gradual rise. We therefore consider that the MR fluid brake step response is the superposition of a fast and a slow response.

To model brake fluid behavior, we formulated the following equation, which is a sum of two first-order delay systems:

$$\triangle\tau = \left\{ \frac{0.4}{1+T_r} + \frac{0.6}{1+T_s} \right\} \triangle\tau_{ref} \quad (2)$$

Here, $\triangle\tau$ is the change in brake torque, $\triangle\tau_{ref}$ is the target change in brake torque, T_r (= 1.0 ms) is the time constant for the fast response, and T_s (= 10.0 ms) is the time constant for the slow response. T_r and T_s were chosen to best fit measurement data with discrete time-steps of 1.0 ms.

C. 2D Passive Type Force Display Device " MR-PLEMO "

" MR-PLEMO " is composed of 2 MR fluid brakes. The overview of " MR-PLEMO " is shown in Fig. 4. The size of the system is 630 wide, 540 deep, and 970 high mm. A handle is attached to the end of the parallel link mechanism. The user controls the handle while watching the PC display. Control input is transferred to the brakes through belt pulleys. The belt pulley system has a speed reduction ratio of 1 : 4. Belts have a glass fiber core and high stiffness. A magnetic field is applied to MR fluid brakes to control force display. Brake control and graphic display were performed on a single PC. ART-Linux allowed us to do real time control. The sampling time of control was set to 0.5 ms.

This system is passive force display system with only brakes, so assured inherent safety. However, it is necessary to ensure not only mechanical safety but also electrical safety, because MR fluid brakes require high current (few A). For electrical safety, we grounded the highvoltage power supply and every MR fluid brake. An isolation circuit is also installed between the DC power supply and the control PC to protect the PC from counter electric current from the power supply in case of runaway.

The position of the operating handle is determined by the rotation angle of the lower link (Link 1) and upper link (Link 2)(see Fig. 5). The length of both links is L = 300 mm. Two incremental encoders were used to measure angles of both links. Four times the base resolution (81,000 pulse/revolution) was used. A coordinate system with the handle as the base is called the xy-coordinate system. Origins of this coordinate system are determined by an initial position when the software is started. A 6 axial force sensor (Minebea OPFT-220N, responsiveness 1 kHz, data output cycle 100 μs) was attached to the handle. The sensor was used to measure multiaxis wheel force.

In order to use passive type systems, users must be able to move their arms by themselves. Passive type rehabilitation support systems for upper limbs therefore target patients in

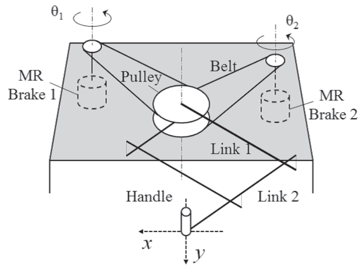

Fig. 5. Conceptual illustration of robot arm part on the 2-D passive force display system

Brunnstrom Recovery Stage (BRS) III or higher (III-VI). The BRS emphasizes synergy movement that develops during recovery from hemiplegia.

III. Force Display Experiments

Experiments with 3 types for force display - vibration, wall surface, and viscous resistance - will be explained in this section. These force display types are needed for the rehabilitation program.

A. Vibration Display Experiment

By applying sinusoid current to the MR fluid brake, sinusoid vibration can be displayed to the user. Vibration frequency f = 100 Hz, 300 Hz were used for the experiment. Brake force F [N] of the sinusoid is defined by the following equation:

$$|F| = 10.0\{0.5 + 0.5\sin(2\pi ft)\} \quad (3)$$

The command for the current value was given to the MR brake to generate the target brake force. Sampling time was 0.5 ms. The handle was moved linearly. Values were measured from the force sensor that was attached to the handle. Figs. 6,7 show values obtained from the force sensor. (The dotted line represents the target brake force derived from (3).) There is some damping and phase delay. In 0.05 seconds, however, each graph shows vibration of 5 and 15 times. This corresponds to 100 Hz and 300 Hz.

B. Wall Surface Display Experiment

Creating an artificial sense of reality for a virtual object is one of the basics of virtual reality technology. To reproduce a wall surface, current is applied to the MR fluid brake when it hits the coordinates of the virtual wall. Resistance makes the user feel as if the handle has hit a wall.

In this experiment, the resistance force of virtual wall appears, when the conditions are

$$x \geq 0.1 \cap V_x > 0 \quad (4)$$

Velocities for the x-directions were denoted as V_x.

Fig. 8 shows hand velocity (x-direction component) in this situation. Fig. 9 shows the value of the force sensor (x-direction component). A, B, C, and D within the graph each represent the following:

- A: From program start to handle gripping.
- B: The hand starts moving toward the wall.
- C: The hand reaches the virtual wall.
- D: The hand moves away from the wall.

At the boundary between B and C, the user hits the virtual wall. At this point, hand velocity becomes 0 and a huge brake force (impulsive force) is rapidly generated. At D, the hand moves away from the wall. No huge brake force is generated at this point.

C. Viscous Resistance Display Experiment

Viscous resistance is displayed by generating brake force opposite to the direction of handle movement. Viscous resistance display is a type of differential feedback. If the response of the brake is poor, brake force cannot be applied smoothly against changes in speed. Because this system uses a fast response MR fluid brake, it can display viscous resistance fields well. Hand movement in a viscous resistance field was observed in this experiment.

In the created application shown in Fig. 10, the screen displays a work area with dimensions 0.2 m × 0.2 m. The target moves from (-0.1,0) to (0.1,0) at a constant speed of 0.05 m/s. Two seconds after software starts, the target moves along the following path: origin → (-0.1,0) → (0.1,0) → (-0.1,0). The handle position is represented as a circle. The user follows the target on the screen (force can be generated in these areas and directions). Viscous resistance [N] in Area I is 60 times [N/(m/s)] the hand velocity [m/s]. Viscous resistance [N] in Area II is 240 times [N/(m/s)] the hand velocity [m/s]. These conditions are written using the following equation:

$$|F| = \mu|V| \quad (if(x' < 0) \quad \mu = 60 \quad else \quad \mu = 240) \quad (5)$$

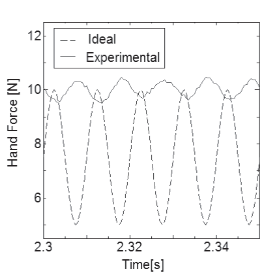

Fig. 6. Sin-curved vibration force display : f=100[Hz]

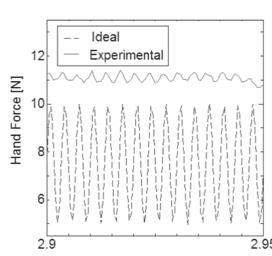

Fig. 7. Sin-curved vibration force display : f=300[Hz]

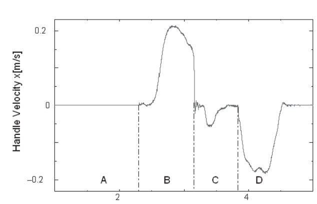

Fig. 8. Handle velocity data when the end effecter contacts with a virtual wall

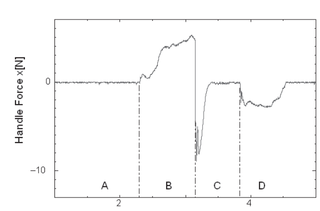

Fig. 9. Handle force data when the end effecter contacts with a virtual wall

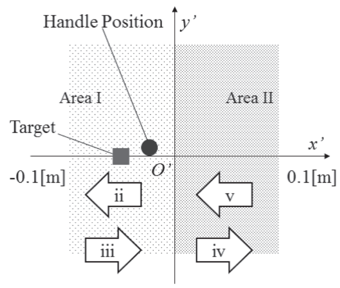

Fig. 10. An application of viscosity force display

where $|F|$ is the length of the velocity vector and μ is the viscous coefficient.

Fig. 11 shows hand velocity (the dotted line represents the velocity of the target, the solid line represents the velocity of the hand) of the subject. Fig. 12 shows multiaxis wheel force from the user (the dotted line is ideal, the solid line is actual). The subject practiced following the target beforehand. i), ii), iii), iv), and v) in the graph represent the following:

- i) From program start to initial target movement.
- ii) Movement from the origin to (-0.1,0) in Area I.
- iii) Movement from (-0.1,0) to the origin in Area I.
- iv) Movement from the origin to (0.1,0) in Area II.
- v) Movement from (0.1,0) to the origin in Area II.

In ii) and iii), resistance is 60 times hand velocity. In iv) and v), resistance is 240 times hand velocity. The user's hand slips when moving from Area II to Area I because of the difference in resistance.

IV. Development of Training Application

We used the basic force displays from the previous section to create a rehabilitation training application.

A. Virtual Maze Training

Wall surface display and viscous resistance display were used to create a training application. Fig.13 shows "virtual maze training." The location of the ball is shown on the screen as a circle. The user goes from the start and works toward the goal. When the ball touches the wall of the maze, resistance from the wall is generated from a wall display algorithm. Some zones contain fluid. Viscous resistance is displayed in these zones. This training program is expected to improve the area of movement of the joints and coordination of the shoulders and elbows.

Fig. 14 shows the trail of the subject's hand. The subject worked toward the goal while making contact with the walls.

B. Painting Erasing Training

Painting erasing training shown in Fig. 15 measures the mobility of the upper limbs, the range of motion, and motor skills. The user traces the picture on the screen by moving the handle. When the whole picture is traced, the picture " disappears and a new picture appears from behind. The time of the trace, the trail of the handle, and the range of motion of the handle are used to evaluate upper limb motor function. In this software the vibration force display is used to display friction on a flat surface.

V. Future Work

In the future, clinical evaluation tests by using such as the above training programs need to be carried out for this system to check whether the system is effective for rehabilitation training.

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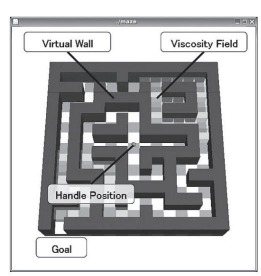

Fig. 13. Training software "Virtual Maze"

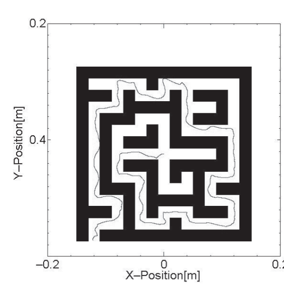

Fig. 14. Trajectory of handle while playing "Virtual Maze"

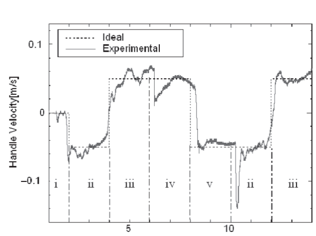

Fig. 11. Handle velocity data on the application of viscosity force display

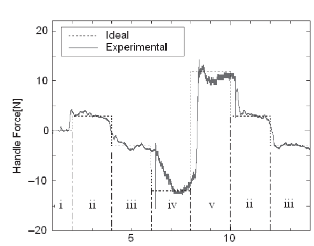

Fig. 12. Handle force data on the application of viscosity force display

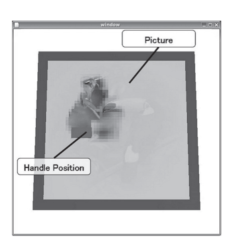

Fig. 15. Training software "Picture-mask erasing"