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A New Hybrid Actuator Approach for Force-feedback Devices

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Abstract— **A new concept of hybrid actuator for haptic devices is proposed. This system combines a controllable magnetorheological brake with a conventional DC motor. Both actuators are linked through an overrunning clutch. Thus, the motor is connected to the handle while the brake can exert a resistive force only in a defined direction. This configuration enables the brake and the motor to be engaged at the same time because the torque imposed by the motor is not canceled by the brake. The concept and its control laws have been investigated using a 1-DOF haptic device. The experimental results show that is possible to combine a powerful brake with a small DC motor. This approach reduces the power consumption, expand the range of forces, achieve global stability in the system providing thereby safety to the user. Besides, the proposed independent control laws enable the actuator to be adaptable in many different haptic applications.**

1. Motivation

Haptic interfaces comprise a wide range of robotic devices intended to display reflective forces which recreate an interaction with a virtual environment. Their most common applications include teleoperation, steer-by-wire systems, chirurgical training devices, etc. In terms of transparency, the use of haptic devices varies from free displacement, requiring minimal friction and inertia, to the virtual obstacle, which supposes the highest displayable stiffness. Thereby, in order to ensure a transparent and realistic rendering, the actuators must cover a wide range of forces.

Usually, haptic interfaces use DC motors to generate interaction forces. This active behavior can represent a potential danger to the user if the interface becomes unstable. Colgate et al. [1] demonstrate that for an active interface high control loop gains can violate stability criteria. Moreover, Gillespie and Cutkosky [2] conclude that active sampled-data systems inject energy into the system in an amount proportional to the displayed stiffness.

In order to guarantee simultaneously global stability and safety, several works focused on passive-based control methods. The term passivity-based-control defines a controller design methodology intended to achieve stabilization by passivation. Colgate et al. [3] introduce the concept of “virtual coupling”. It consists in a virtual spring-damper model placed between the simulation and the device to restrict the impedance of the interface. Adams and Hannaford [4] use two-port network theory to determine optimally virtual coupling parameters. Hannaford and Ryu [5] present a passivity-based controller as a solution to ensure stability. The control scheme includes a dissipative element implemented to satisfy the passivity condition (the interface does not create energy). These techniques are efficient to assure stability, however the compromise between stability and performance bounds the interfaces to limited stiffness and velocity.

The main advantage of a DC motor is that it can produce torque in both directions with a relatively fast response time. These actuators are usually linked to gearboxes with elevated reduction ratios to display high torques. As a result, friction forces between the gears can induce undesirable vibrations at the end-effector damaging the transparency of a haptic rendering. Furthermore, motors have to work in very different conditions for their nominal operating points in the torque-velocity plan, which increases the energy consumption. While the ratio torque-to-weight increases with the transmission ratio, bandwidth, efficiency and quality of produced forces are inversely proportional to it [6].

In order to achieve stability and to increase performance of the system, active interfaces with passivity-based control scheme can be replaced by passive actuators. Since these devices cannot produce energy, passive interfaces are at the same time intrinsically stable and safe. This configuration can expand the range of motion [7] and applicable forces. Notwithstanding, it is not possible to restore any energy to the user.

The most common passive actuators used in haptics comprise rheological brakes, dampers and powder brakes. Magnetorheological-based (MR) brakes, for example, provide high controllability, fast response time, very low power requirements and a high torque density. The miniature MR brake developed by Periquet and Lozada [8] can produce a torque of 0,03 to 1,7 Nm and consumes 27 Watts. Compared with a commercial DC motor (maxon RE-25), it represents 51 times more torque for the same volume. In terms of power, the MR brake presents a ratio torque/power-volume 38 times superior to the motor. In a portable haptic device, where power consumption and volume minimization are a major constraint of design, this kind of actuator is a promising solution.

In terms of stability and range of forces, we easily conclude that brakes and motors are complementary. In this paper a novel concept of actuator for haptic applications is presented. A DC motor has been combined with a MR brake and a freewheel mechanism. The brake is used to dissipate energy and the motor is enable to create a limited active behavior, in a configuration when the effort produced by the motor is not canceled by the brake. To understand its functioning Section 2 presents a more elaborated review of brake-based haptic devices and how its passive behavior can affect haptic renderings. Subsequently, the new actuator concept and its

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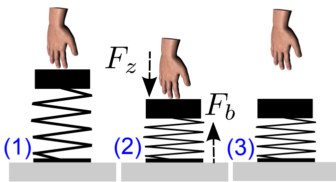


Fig. 1. Spring simulation using passive actuators: the brake provides the required stiffness only during the compression phase.

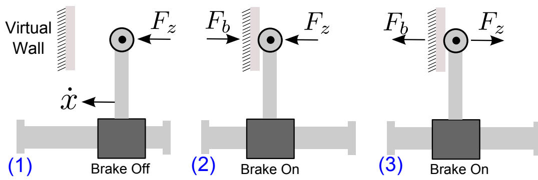


Fig. 2. Stick phenomenon in the simulation of a virtual wall using only brakes: the user impose a force F_z to move the handle, when the virtual wall is attained, the brake imposes a resistive force $F_h$which is always opposed to F_z.

respective control laws are presented.

2. Brake-Based Haptic Interfaces drawbacks

Brake-based haptic devices are intrinsically stable, represent no danger to the user and reduce energy consumption. But these actuators are intrinsically dissipative and the impossibility to create energy can produce some inconveniences which can affect the quality of an haptic rendering. The limitation comprises the impossibility of the interface to create forces in arbitrary directions, the stick phenomenon in the simulation of virtual wall and the impossibility to restore energy as presented by the following examples.

Using brakes, the simulation of elastic elements can be displayed in one direction only. Consider the simulation of a virtual spring using a 1 degree-of-freedom (DOF) passive haptic interface of Fig. 1. The user imposes a force F_z to compress the spring (1). The brake creates a reactive force F_b proportional to the displacement (2). When the user releases the handle (3), it stays at the compressed position and the brake remains activated. Moreover, during (2) if the user's force becomes inferior to the reactive force ($F_b > F_z$) the decompression phase of the spring can not be displayed.

Another limitation of passive interfaces is illustrated in Fig. 2. Consider now a 2-DOF passive interface that simulates a virtual wall. If the handle does not touch the wall, the user should be able to move it freely (1). When the end-effector reaches the wall the brake is activated (2). Due to the response time of the system the end-effector penetrates the wall until the forces are balanced. When the velocity becomes zero, according to Karnopp's stick-slip model, the braking force is always opposed to the external force ($F_b = -|F_h|\, sgn(F_z)$ where F_h is the brake control torque), as a result, if the user wants to turn the handle back the brake will impose a resistive force (3) until the handle comes out of the wall. This behavior can be perceived by the user as a stick phenomenon.

Consider now a 2-DOF passive force-feedback interface presented in Fig. 3 composed by two independents linear brakes. In a 2-DOF device, the strict dissipative behavior of

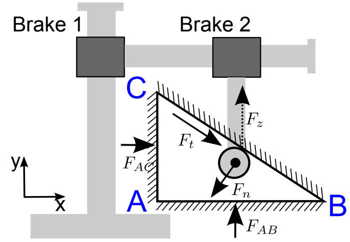


Fig. 3. 2-DOF brake-based interface: brake 1 can impose a resistive force for the displacement of the handle along the y axis while brake 2 can control the movement in the x axis.

the actuators impairs its ability to generate forces in arbitrary directions [9] [10].

If both brakes are released, the handle can move freely. If brake 1 and 2 are activated, it is possible to display a resistive force aligned with the displacement in every possible direction. Suppose that the virtual environment simulates a frictionless triangular wall limited by the segments $\overline{ABC}$. In order to simulate a constraint along the $\overline{AB}$ segment, brake 1 can be activated to induce a reaction force F_{AB}. The same method is used to simulate a constraint in the segment $\overline{AC}$ by the brake 2 inducing F_{AC}. If the user moves the handle along the y axis, (imposing a force (F_z)), when the handle touches the segment $\overline{CB}$, a normal reaction force (F_n) can be controlled by engaging both brakes. At this point, the resultant force and the lack friction have to induce a displacement along the segment $\overline{CB}$ in the direction of the point C. Since brakes can exert a force only against the velocity, when the handle moves along the inclined segment, an undesirable tangential force appears (F_t), as a consequence the normal force F_n cannot be simultaneous controlled. The brakes are consecutively engaged which takes the form of small steps, certainly perceived by the user.

3. Hybrid Interfaces

In order to solve these limitations, a motor can be linked to the brake to produce an active behavior. An and Kwon [11] propose a hybrid configuration where a motor is used to reduce the inherent friction of the system (active force feedback), and a controllable MR brake is simultaneously used to display a simulated friction (passive force feedback). Nam and Park [12] use a passive actuator to exert the reflective forces whereas an active actuator is just used to compensate undesirable back-driven forces. Another hybrid approach, also proposed by An and Kwon [13], who used a DC motor to display a virtual stiffness and a controllable brake to display a virtual damping. As a consequence, the DC motor provides a force feedback while the brake provides stability.

More specifically, Kwon and Song [14] have developed a 2-DOF hapic device comprising MR brakes and motors in each link. They concluded that when brakes and motors are linked together, the direction of the reflective force depends on the force imposed by the user. This is because the brake can exert only a reaction force against the motion. When brakes and motors are linked, the effort of the brake and the motor can be easily added to impose a resistive force, but at the same time, if the handle is released, the active effort is naturally canceled by the brake. In order to solve the two presented primary limitations, we have proposed in [15] a 1-DOF haptic device composed of a MR brake and a DC motor. To control the system the controller determines if the interface has to dissipate or create energy comparing the velocity, the desired force, and the interaction force. If the desired torque is opposed to the velocity and inferior to the torque imposed by the user (energy dissipation), the brake is activated, otherwise, only the motor is used. Conti and Khatib [16] propose an elegant solution combining a brake, a spring and a motor. The actuators are linked together using an angular spring. Thereby the brake is used to control the amount of stored energy in the spring while the motor is used to eliminate the error between the desired and applied torque. The total torque applied by the actuator is the sum of the imposed torque by the motor and the torque stored in the spring.

The new proposed approach is designed to combine the brakes and motors using a configuration where the active effort exerted by the motor is not canceled by the brake. As a consequence, the evoked limitations of passive actuation can be overcome using appropriated control laws.

4. New actuation concept

The new actuation concept combines a controllable magnetorheological brake with a DC motor and both actuators are associated using a freewheel. Therefore, the brake is used to dissipate energy and the motor used to create an active behavior. Fig.4 shows the prototype configuration.

Supposing that the brake is activated: The MR brake is linked to a freewheel mechanism, that transmits the resistive brake torque to the handle only in a given direction. If the user turns the handle in the clutched direction, the brake imposes a resistive torque. If the handle is turned in the other direction, it can move freely. Notwithstanding the motor is connected directly to the handle and it can exert a torque in both directions.

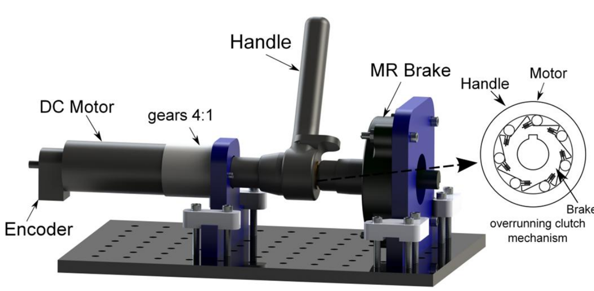


Fig. 4. Hybrid haptic interface based on an unidirectional MR brake: The handle is direct linked to a DC motor and its axis is linked to a MR brake through a freewheel mechanism. The torque of the brake can henceforth be transferred to the handle in only one direction. Only the position is measured using an incremental encoder.

The brake is a Lord RD2078, exploited until 400 mNm. The motor is a Maxon RE40, with a nominal torque of 54 mNm coupled with a reduction gears with a transition ration of 4. The freewheel mechanism measure 16 mm of diameter and 23 mm of length. It can transmit 20 Nm of torque. An

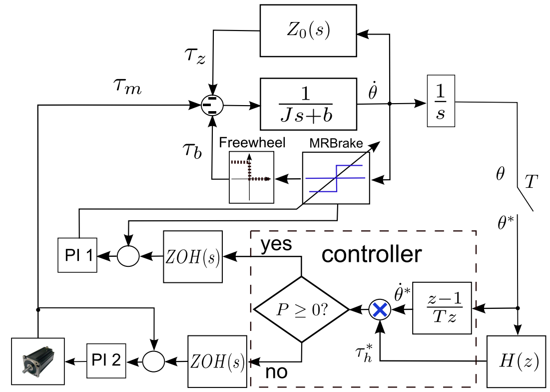


Fig. 5. Actuator control scheme: Only the position θ is measured and its value is used by $H(z)$, a function that represents the virtual environment and calculates the desired torque $\tau_h^* = H(z)\theta(z)$. The symbols marked with an asterisk are discrete variables.

incremental encoder with 4096 pulses per revolution is used to measure the position. Note that the device is asymmetrical and can work only in one direction.

An analysis of the power flow in the device is used to control the actuator. By definition, the interface dissipates energy if power flows from the user to the interface. This condition can be determined by observing the direction of the desired torque (τ_h^*). If the desired torque is opposed to the measured velocity the device should produce a resistive torque on the user: the haptic device dissipates energy and the brake must be activated. Moreover, if the torque and the velocity have the same direction, the motion is created by the interface: the haptic device creates energy and the motor has to be engaged.

The power flow in the device is given by:

$$P = -\tau_h^* \dot{\theta} \tag{1}$$

Equation 2 presents the control laws used to control the interface without considering the freewheel mechanism.

$$\begin{bmatrix} \tau_m \\ \tau_b \end{bmatrix} = ZOH(s) \begin{cases} \begin{bmatrix} 0 \\ |\tau_h| \, sgn(\dot{\theta}) \end{bmatrix} & P \geqslant 0 \\ \begin{bmatrix} \tau_h \\ 0 \end{bmatrix} & P < 0 \end{cases} \tag{2}$$

Where τ_m and τ_b are the torque imposed by the brake and the motor respectively. According to a sampling period T:

$$ZOH(s) = \frac{1 - e^{-sT}}{s} \tag{3}$$

Fig. 5 shows the global control scheme. The mechanical device is represented as an inertia J with some viscous friction b. The user is modeled as an impedance noted $Z_0(s)$ and his applied torque on the device is noted τ_z. Both actuators are controlled in force by two analog proportional-integral controllers (PI 1 and PI 2) and the freewheel mechanism is represented as a nonlinear constraint. The global system is controlled by a microcontroller $8051F120$ operating at 99,3 MHz. The conversion between discrete and continuous domain is modeled by a zero-order-hold function ($ZOH(s)$).

The global stability of the system can be investigated by an analysis of the passivity. An intuitive statement of passivity is that the total energy of the device is never as great as the total energy created by the user ($-\int_0^t \tau_z(u)\dot{\theta}(u)du \geq \frac{1}{2}J\dot{\theta}^2$). It is verified by the follow Equation:

$$-\int_0^t S(u)f(\tau_h(u))\dot{\theta}(u)du - \int_0^t (1-S(u))\tau_h(u)\dot{\theta}(u)du + \int_0^t b\dot{\theta}^2(u)du > 0 \; \forall t \geq 0 \quad (4)$$

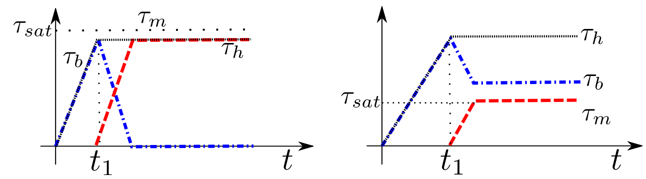
Where $S(u) = 1$ if only the motor is enabled and $S(u) = 0$ if only the brake is activated. The function $f(\tau_z)$ represents the saturation of the motor and is written $f(\tau_z) = \alpha(u)\tau_h$ where $\alpha(u) = f(P, \tau_h)$. The third term is the energy dissipation due to viscous friction. The two first are the torque of the motor and the brake respectively and after some mathematical manipulation it can be simplified as $-\int_0^t \tau_h(u)\dot{\theta}(u)du - \int_0^t S(u)\left[f(\tau_h(u)) - \tau_h(u)\right]\dot{\theta}(u)du$. Where $-\int_0^t \tau_h(u)\dot{\theta}(u)du$ is the passivity of the virtual environment. The second term can be rewrite as $\int_0^t S(u)\left(\alpha(u)-1\right)P(u)du$. For a dissipative behavior, the motor can be used to dissipate energy, thus $0 \leq S(u) \leq 1$ and the controller fixes $\alpha = 1$. For an active behavior, $S(u) = 1$ and $P < 0$, the active torque should be bounded by setting $0 \leq \alpha(u) < 1$. Thus $\alpha(u) - 1 \leq 0$ and $(\alpha(u)-1)P(u) > 0$, the expression is positive and the interface is guaranteed stable.

To overcome the limitations of passive interfaces presented in the Section 2, two main control methods based on this control methodology are proposed. On the first case, the control laws are intended to minimize the actuation of the motor to reduce energy consumption. The motor is strictly used to restore energy with one exception: it can be engaged if the velocity becomes zero. Thus, the desired torque is simultaneously assumed by the brake and/or the motor. This configuration enables the system to become active if the user releases the handle and is able to eliminate the stick phenomenon in the simulation of a virtual wall. The second control method defines a minimum level of participation of the motor in the applied force. The brake is activated only when this limit is exceeded. This method enables the actuator to display resistive forces in arbitrary directions when this limit is not reached.

To validate the proposed actuator approach and to develop the appropriated control laws, the virtual environment has been defined as a simulation of an angular spring ($H(z) = K$, where K represents the stiffness of the spring). In both methods, the maximum active torque has been arbitrary fixed at 80 mNm.

5. Gradual brake/motor transition

This method establishes a special condition in the control law when the velocity is zero. There are two situations. First, the user has released the handle: On this case the motor is activated to turn the handle back. Second, the user imposes an



(a) motor not saturated ($\tau_{sat} \geq \tau_h$) (b) motor saturated ($\tau_{sat} < \tau_h$)

Fig. 6. Control method using brake/motor transition: Supposing a passive behavior, at $t = t_1$ the velocity becomes zero. In the first case, the desired torque (dotted line) is ensured by the motor (dash-doted line τ_m), in the second case, the motor is saturated and the brake (dashed line τ_b) is simultaneously engaged.

effort opposed to the reactive force with the same amplitude: the motor is activated and when the effort imposed by the user becomes inferior to active torque, the device has an predominant effect on the user and the interface becomes active.

The control law works as follow: when the velocity is zero the brake and the motor are simultaneously activated. The desired torque is primordially assumed by the motor. If the motor is saturated, the difference is compensated by the brake. Thanks to the freewheel mechanism the reactive force of the motor is not canceled by the brake, and if the operator releases the handle it can move freely according to the applied force.

This transition can impose an error between the desired and imposed torque which can induce undesirable vibrations at the handle. Thus, it is necessary to implement a gradual transition controller. When $\dot{\theta} = 0$, the brake is gradually turned off, while the active torque is simultaneously and proportionally increased. This transition controller takes the form of a non-linear time-variant element γ determined by:

- Whether the motor is activated: $\gamma = 1$;
- Whether the brake is activated: $\gamma = 0$;
- During the transition brake/motor: $0 < \gamma < 1$. The γ variable is increased by δ at each period T.

The maximal active torque can be set as $\tau_{sat} = i_{max}k_i$, where i_{max} is the maximal admissible current on the motor and k_i represents the characteristic torque/current constant of the motor. Fig. 6 shows its theoretical implementation.

If $-\tau_{sat} \leq \tau_m \leq \tau_{sat}$, the control law with gradual brake/motor transition controller is given by:

$$\begin{bmatrix} \tau_m \\ \tau_b \end{bmatrix} = ZOH(s) \begin{cases} \begin{bmatrix} 0 \\ |\tau_h|\, sgn(\dot{\theta}) \end{bmatrix} & \{P > 0 \\ \begin{bmatrix} \tau_h \\ 0 \end{bmatrix} & \{P < 0 \\ \begin{bmatrix} \gamma\tau_h \\ |\tau_h - \tau_m|\, sgn(\dot{\theta}) \end{bmatrix} & \{P = 0 \end{cases} \quad (5)$$

Using a similar analysis, another gradual transition can be implemented to control the transition motor/brake.

Fig. 7 presents the experimental results using the first control method based on gradual transition. At $t = 0$ the spring is in its initial position. The user begins to compress the spring, thus, it induces a resistive torque in the virtual environment which is opposed to the velocity characterizing a dissipative behavior: the power is positive and the compression phase of the spring should be simulated by the brake. The brake

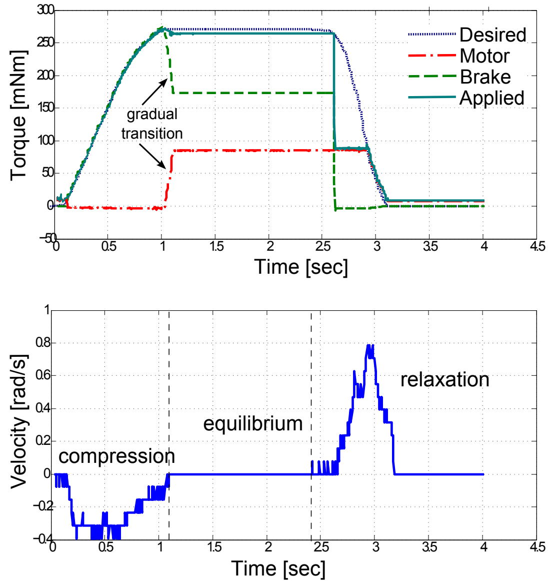


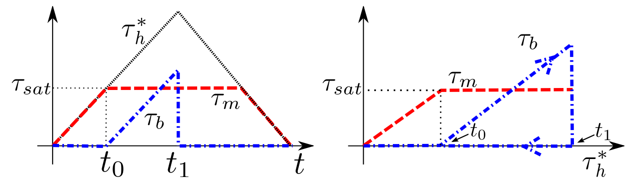
Fig. 7. Experimental results using power flow based controller and gradual transition method.

follows then the desired torque until $t = 1,1s$. At this moment, the speed becomes zero. According to the control laws, the motor must be activated: the desired torque is transferred to the motor. Since $\tau_h > \tau_{sat}$ the motor is activated until its saturation and the difference is assumed by the brake ($\tau_b = \tau_h - \tau_{sat}$). The transition is managed by the gradual transition controller. Note that in the direction of the compression of the the spring the desired torque is respected. Thanks to the freewheel mechanism the active torque provided by the motor is not canceled by the brake. Now, if the user releases the handle, or if he imposes an effort inferior to the active torque, the handle can turn back ($\forall t \geq 1.1s$). The velocity remains zero until $t = 2.4s$ when the user turns the handle back and the velocity is inverted. At this point, the velocity and the desired torque τ_h^* have the same sign: power becomes negative. This means that the device must create energy. Thus, the motor simulates the relaxation phase of the spring while the brake is turned off.

6. Motor Saturation Limit

The method proposed in the Section 4 is based on the power flowing in the interface. The brake is used to restore energy while the motor is used to impose a resistive torque. One exception occurs when the velocity is zero: the brake and the motor are simultaneously activated. This transition must be supervised by a gradual transition controller to avoid vibrations. In contrast, this method allows energy dissipation using the motor. To assure a transparent transition we note easily that an interesting solution is to maintain the motor always activated.

In the second proposed method, we define a minimum contribution of the motor in the applied force, this point corresponding to the motor saturation point τ_{sat}. If the desired force $H(z)\theta(z)$ is inferior to τ_{sat}, only the motor is activated, but if the desired force is greater than the saturation limit, and



(a) applied torque versus time (b) applied versus desired torque

Fig. 8. Control method regarding motor saturation point: Only the motor is used until its saturation. Supposing a passive behavior between $0 \leq t \leq t_1$. The desired torque is assumed by the motor, at $t = t_0$ the motor is saturated and the brake is simultaneously engaged. At $t = t_1$ the velocity is inverted (power becomes negative), in consequence the brake is turned off.

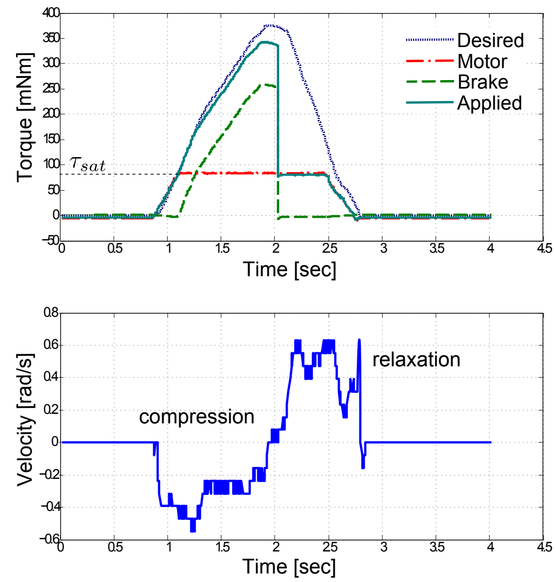


Fig. 9. Experimental results using power flow-based controller after motor saturation point.

in the case of passive behavior, the brake is simultaneously activated. In other words, the energy flow controller works only when the motor is saturated. The transition becomes naturally continuous.

The control law is then defined by:

$$\begin{bmatrix} \tau_m \\ \tau_b \end{bmatrix} = ZOH(s) \begin{cases} \begin{bmatrix} \tau_h \\ 0 \end{bmatrix} & \left\{ \begin{array}{c} \tau_h < \tau_{sat} \\ or \\ P < 0 \end{array} \right. \\ \begin{bmatrix} \tau_{sat} sgn\left[\tau_h\right] \\ \left|\tau_h - \tau_m\right| sgn(\dot{\theta}) \end{bmatrix} & \left\{ \begin{array}{c} \tau_h \geq \tau_{sat} \\ and \\ P \geq 0 \end{array} \right. \end{cases} \tag{6}$$

Fig. 8 shows a representative functioning of this control method. Using this method, for large forces, the haptic feedback is provided by the brake while for forces up to motor saturation point, the rendering is always provided by the active actuator. To respect safety concerns, the torque applied by the motor is limited according to the application whereas the brake can exert significantly more important torques.

The results of the second method are presented in Fig. 9. The spring is in its initial position at $t = 0$. The user moves the handle to begin the compression phase. It represents a dissipative behavior. Different from the precedent method, the compression phase will be simulated by the motor until its saturation at $t = 1,3s$ (when $\tau_e = \tau_{sat}$) while the brake remains deactivated. From this point, the difference between the desired torque and the maximum torque of the motor is compensated by the brake ($\tau_b = \tau_h - \tau_{sat}$, with $\tau_{sat} < \tau_b$). When the velocity is inverted, at $t = 2.0s$, the brake is turned off while the motor remains activated.

The only difference compared to the method based on gradual transition appears when the interface dissipates energy. In the first method, the interface dissipates energy using only the brake, and in the second case by means of the brake and the motor. The second method is destined to 2-DOF devices: The active torque is not canceled by the brake and does not depend of the direction of the force imposed by the user. In a 1-DOF device, there is no limitation regarding direction forces. Thus, it is not necessary to dissipate energy using the motor. Thereby, the first method is more suitable in this case, because it can reduce the power consumption.

7. Conclusion

This actuation approach is based on a powerful magnetorheological brake combined to a DC motor. Thanks to overrunning clutch placed between the actuators, the torque of the motor is not influenced by the brake and it can be transmitted direct to the handle. Thereby, the actuators can be activated at the same time to exert feedback torques.

Experimental results suggest that this configuration can solve the limitation of passive actuators like stick phenomenon, impossibility to create an active behavior and the exertion of efforts in arbitrary directions. Besides, the actuator design enables us to combine a powerful brake with a small DC motor. The brake is used to display high forces while the motor exerts a limited active behavior. Thus, safety concerns can be satisfied without damaging the performance of the device.

Two main control strategies have been developed. The first method restricts the motor to impose an active behavior or to dissipate energy only when the velocity is zero. It is designed to minimize the energy consumption and is designed to 1-DOF haptic interface. In the second method, the motor is always activated to assure a continuous transition and to assist the device to display forces in arbitrary directions. This method is designed for a multiple DOF haptic interfaces. Furthermore, the motor can dissipate energy and the maximal resistive torque is the sum of the torque of the brake and the motor. Both methods are based only on two basic pieces of information: the measured velocity and the force calculated by the virtual environment. Thus, the control is independent of the simulation and does not need any measure of interaction force. As a consequence, the actuator approach and its control methods are adaptable in a large range of force-feedback devices.

A complete system requires two independent brakes and a motor. The torque/volume and the torque/volume-power ratios are expected to be 10 times and 200 times superior than a volume equivalent DC motor respectively.

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