Dual Differential Rheological Actuator for Robotic Interaction Tasks

P. Fauteux, M. Lauria*, Member, IEEE*, M.-A. Legault, B. Heintz and F. Michaud, *Member, IEEE*

Abstract— **Robots fail to perform complex manipulation or locomotion tasks when using simple force or motion controllers applied to classic actuators. Stability and safety issues arise for reasons such as high output inertia and the non-collocation of sensing and actuating transducers. This paper presents a new actuation concept, integrating a DC motor and two differentially coupled magnetorheological brakes, promising safe and versatile interaction capabilities. This paper focuses on the underlying mechanism and a case study with a proof-of-concept prototype.**

I. INTRODUCTION

MOST modern robotic systems are fast and repeatable position controlled machines. However, despite extensive R&D efforts, they mostly remain confined to controlled areas where they execute specific pre-programmed actions. Furthermore, they still display limited performances in tasks such as grinding, polishing, surface following and complex assembly. Moreover, even if many economically interesting man-machine interaction applications have been identified (e.g., physical therapy, training assistance, surgery assistance, manual tasks teaching, sport training, orthesis and prostheses motorization, haptics and teleoperation of interacting machines), very few have been implemented successfully.

Over the last 25 years, some researchers tried to identify and revise design paradigms with one objective in mind: to create robotic systems capable of versatile and safe interactions, which led to the development of interaction control theory [1]. Unfortunately, classic actuators proved to be unfit for its usage primarily because of high output impedance (inertia and friction) and because of the non-collocation of sensing and actuating transducers. Hence, innovation is required so that the wide and growing range of industrial and service applications can be adequately supported.

A safe and versatile actuator, fit for a variety of interaction tasks, must possess at least four basic characteristics: 1) high force or torque density; 2) sufficient bandwidth; 3) very low output impedance; and 4) high-fidelity force display capability. Figure 1 illustrates, qualitatively, the performance of classic actuators with regard to these metrics. In this figure, characteristics 3 and 4 are merged into the "quality of force produced", which is an appreciation of the ability to output a desired force despite output motion. As shown, no classic actuator simultaneously exhibit all the necessary characteristics of a high performance actuator fit for safe and versatile interaction.

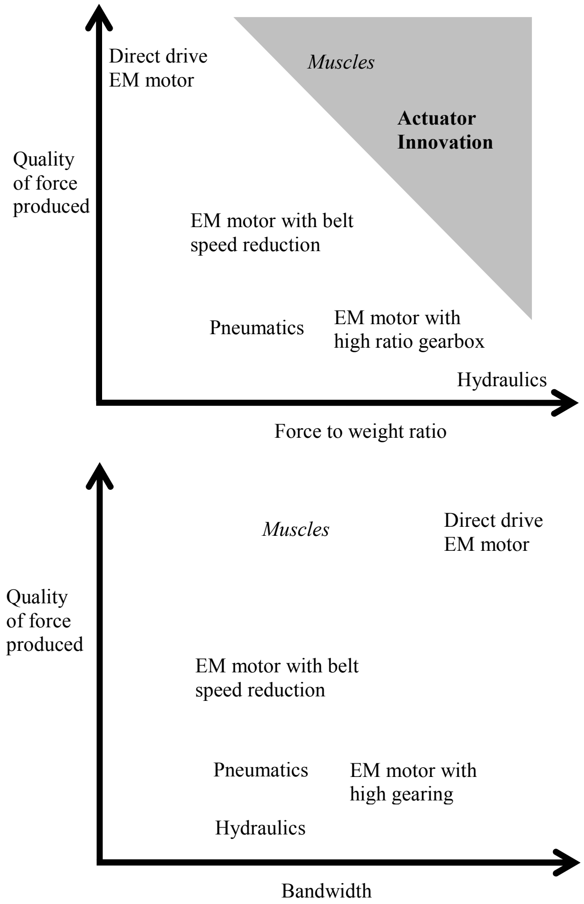

Fig. 1. Quality of force produced versus force to weight ratio (up) and versus bandwidth (down), for classic actuators.

The objective of this project is therefore the development of a novel actuation concept that enables high performance safe and versatile interaction. This paper briefly reviews existing actuators designed for interaction tasks and introduces the Dual Differential Rheological Actuator (DDRA) concept which uses a DC motor and two differentially coupled magnetorheological (MR) brakes to create a high performance force source. Results obtained using a proof-of-concept prototype are presented and analyzed.

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Philippe Fauteux is with the Department of Mechanical Engineering, Université de Sherbrooke, Sherbrooke, Québec Canada J1K 2R1 (corresponding author, phone: 819 821-8000 x 62893; fax: 819 821-7937; e-mail: philippe.fauteux@usherbrooke.ca).

Michel Lauria, Marc-Antoine Legault, Benoît Heintz and François Michaud are also with the Department of Electrical Engineering and Computer Engineering, Université de Sherbrooke, Sherbrooke, Québec Canada J1K 2R1 ({philippe.fauteux, marc-antoine.legault, benoit.heintz, francois.michaud}@usherbrooke.ca.

II. ACTUATORS DESIGNED FOR INTERACTION TASKS

Existing actuators designed for interaction tasks can be categorized by the following:

- *Force Feedback Actuators (FFA).* They comprise a stiff force sensor placed in series with a classic high impedance actuator such as a geared electromechanical (EM) motor. The interaction is controlled using force feedback. Unfortunately, the non-collocation of the sensing and actuating transducers limits stable feedback gains and stable interaction bandwidth [2]. Furthermore, the high impedance can be a threat to safety.
- *Impedance Controllable Direct Drive Actuators (DDA).* Direct drive EM motors are usually low inertia devices which have a known relationship between the winding current and the output force. A fast and inherently stable force control can be achieved using a current feed-forward scheme. However, because no gearbox is used, the torque to weight ratio is small and greatly limits the range of possible applications [3].
- *Series Elastic Actuators (SEA).* They use a compliant element placed between a high impedance actuator and a force sensor. By doing so, large amplitude bandwidth is traded for lower apparent inertia, better force resolution, improved control stability and better impact tolerance [4].
- *Differential Elastic Actuators (DEA).* Their working principle is similar to the SEA, but the use of a mechanical differential provides a simplified integration, especially for rotational actuators [5].
- *Variable Stiffness Actuators (VSA).* Most VSA make use of two non-linear mechanical springs working in an antagonistic configuration to provide a mechanical variation of the output stiffness [6]. The resulting actuators are inherently stable and impact tolerant. The main drawback is mechanical complexity.
- *Parallel Coupled Micro-Macro Actuators (PaCMMA)* and *Distributed Macro-Mini (DM_2) Actuators.* The PaCMMA and the DM_2 actuator use a high power SEA in parallel with a low power DDA. The SEA contributes for “low frequencies and high amplitude” forces while the DDA actuator contributes for “high frequencies and low power” forces. The system is controlled in a closed-loop fashion using a force sensor at the output. The dynamic performances are improved compared to the SEA, but complexity and volume are increased [7][8].
- *Variable Damper Actuators (VDA).* These actuators use a serially or differentially coupled rheological fluid clutch placed between a high impedance actuator and the load. The variable output force is obtained by modulating the clutching torque. Advantageously, the environment is isolated from the inertia of the high impedance actuator. However, to reverse output force, the input speed must be reversed, thus limiting the bandwidth. Also, the minimum clutch friction limits the capabilities to display very small forces [9] [10].

Integration has so far been a major issue hindering the widespread use of actuators designed for interaction tasks. In such tasks, convenient geometries and small volumes are usually desired. Most proposed concept still struggle to deliver high performance in a convenient package.

III. SEMI-ACTIVE ACTUATORS AND MR BRAKES

Semi-active actuators are devices which can only dissipate mechanical energy, such as friction brakes, magnetic powder brakes and hysteresis brakes. When compared to active actuators with similar forces, many semi-active actuators are smaller, lighter and display lower output inertia. The drawback is that, since mechanical energy can not be generated, they are not alone sufficient for versatile interaction. In this paper, we limit our study to MR fluid brakes.

The rheological behavior of MR fluids is modified by the presence of magnetic fields. When the fluid is sheared, this change is manifested by the development of a yield stress that is more or less proportional to the magnitude of the field [11]. This is exploited in MR brakes, which use one or a plurality of interspersed rotor and stator blades to shear the fluid, as shown in Figure 2. Multiple blades increase the shear area and make it possible to produce large forces. The right part of Figure 2 shows typical output forces (F) versus magnetic field strength (H) and velocity (v) for such devices. B and F_f are viscous and dry friction terms. Note that a stiction phenomenon is visible at low speeds. However, if there is sufficient motion between the plates, the output force can be approximated using Equation 1 where F_y is the field dependant yield force which can be modulated using a simple tension or current feed-forward control scheme [11].

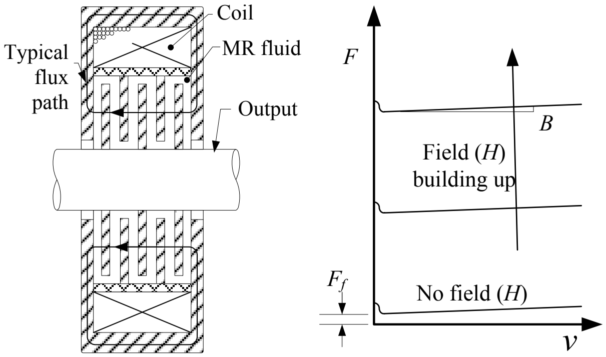

Fig. 2. MR rotary brake (left) and typical curves of a brake force versus field strength and velocity (right).

$$F = (F_y + F_f)\,\mathrm{sgn}(v) + Bv \tag{1}$$

Well designed MR brakes display high torque to weight ratio, low inertia, high bandwidth, wide dynamic torque range and low power consumption. They can furthermore be fabricated at a limited cost if the geometry is kept simple. For these reasons, they were chosen for our first implementation of the DDRA actuator concept.

IV. THE OPPOSED SEMI-ACTIVE ACTUATORS CONCEPT

The Opposed Semi-Active Actuators (OSA) concept uses two identical semi-active clutches being driven at the same velocity but in opposite directions by an external velocity source [12]. Both semi-active actuators outputs are connected together to form the system's output, as illustrated in Figure 3. In this figure, MR clutch 1 controls the clockwise (CW) torque while MR clutch 2 controls the counterclockwise (CCW) torque.

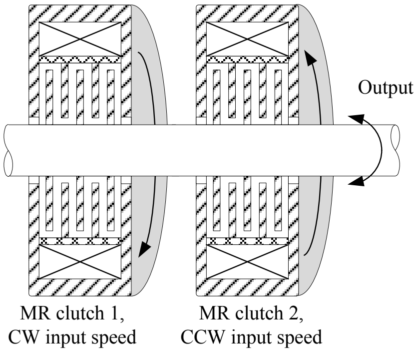

Fig. 3. Opposed Semi-Active Actuators (OSA) concept.

In addition to the fact that the load is isolated from the inertia of the velocity source, many advantages come with opposing two identical semi-active actuators. Because of the symmetry of the design, dry friction is cancelled and is not transmitted to the output. Viscous drag is also balanced when output speed is zero. Even stiction is eliminated because there is always a relative motion in the clutches. Because of these advantages, combined with the fact that forces can be controlled by modulating the feed-forward tension or current to both semi-active actuators, the OSA can act as a high performance inherently stable force source.

V. THE DUAL DIFFERENTIAL RHEOLOGICAL ACTUATOR

In a MR clutch, there is one input rotating member and one output rotating member. The magnetic field is generated either by a rotating coil connected through a slip ring or by a stationary coil surrounded by a fixed magnetic flux guide. In comparison, MR brakes are smaller and simpler since there is only one rotating member.

Because of the use of clutches, the OSA is complex to integrate and a relatively large inertia must be put into motion by the input velocity source. These drawbacks can be significantly reduced by using two differentially coupled brakes instead of the two clutches. Differentials are devices possessing three ports among which force is distributed following a know relationship. Any speed reducer can be used as a differential. In this section, levers are used to introduce the DDRA concept, but only as an analogy to other rotational mechanisms.

This DDRA is conceptually illustrated in Figure 4. A velocity source (not illustrated) moves the inputs ports O_1 and O_4 at velocities v_m. Ports O_3 and O_6 are linked together and form the system's output while ports O_2 and O_5 are connected to the brakes that control the pulling or pushing output force (F_{out}). Because of the differential, a known relationship exist between the braking forces (F_1 and F_2) and the output force. For example, if the speed reduction ratio (R) is large enough, the output force is almost the same as the braking force. Equation 2, derived from the free body kinetic equations of the system and (1), describes this output force F_{out} as a function of the speed reduction ratio R, the output velocity v_{out}, the brakes viscous damping coefficient B and the brakes controllable forces F_{y1} and F_{y2}. Interestingly, the output force is simply a linear combination of the braking forces F_{y1} and F_{y2} and a small damping term.

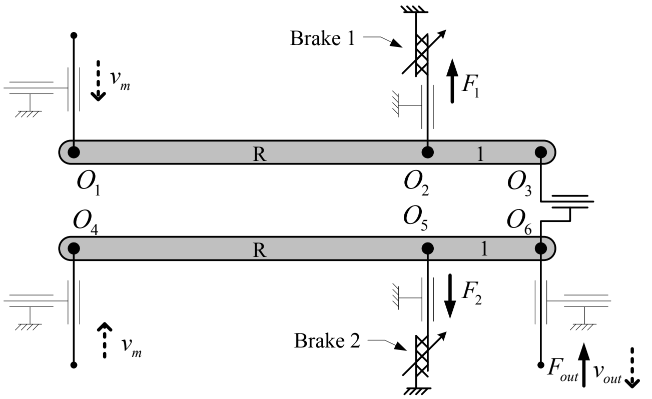

Fig. 4. Dual Differential Rheological Actuator concept illustrated using the lever analogy.

$$F_{out} = \left(\frac{R}{R+1}\right)\left(F_{y2} - F_{y1} - 2\left(\frac{R}{R+1}\right)Bv_{out}\right) \qquad (2)$$

The main advantages expected from the concept, partly inherited from the OSA concept, are listed below:

- Because MR fluids react to a magnetic field within milliseconds [11], forces could be controlled with a large bandwidth. The design is thus potentially suitable for fast force, impedance or position control.
- Output impedance can be exceptionally low because it is decoupled from the velocity source. A low inertia actuator performs better at controlling low forces and impedances. It is also a criterion for the safety of interactions: large inertia is one of the main reasons why robotic technologies are still confined to controlled areas [8]. Furthermore, small inertia improves the ability to accelerate and decelerate quickly and provides faster movement and increased productivity.
- The DDRA concept potentially displays a wide dynamic force range. In geared motors, the transmission adds a lot of noise on the force output. This noise comes from kinematic imperfections, backlash, stiction and non-linear friction. In the proposed concept, the output is linked almost directly to the brakes. Consequently, if the braking forces can be controlled accurately over a wide dynamic range, the DDRA will display high-fidelity force control over a wide dynamic range.

- The proposed concept could eventually be fabricated at a reasonable cost because the decoupling effect previously mentioned makes it possible to use a low quality input velocity source. This motor can be characterized by a large inertia and large time constants Furthermore, the associated gearing can present a lot of non-linear friction. None of these are transmitted to the actuator output. Additionally, the gearing can be machined with large tolerances because the backlash is eliminated because of the internal opposition of forces.
- The actuator is open-loop controllable, which means that no expensive torque sensor is necessary and that the control electronics can be simple. Moreover, because it does not rely on force feedback, it is not vulnerable to the loss of stability when structural modes interact with the feedback loop. For this reason it was reported that this approach should be used whenever possible in interaction control [13].
- The design is impact tolerant. Any excess energy is dissipated by the brakes. The output force is always controlled, even during impact events.
- For some applications, multiple DDRA could be powered by a single mechanical bus conveying the mechanical power from a single velocity source, thus lowering overall complexity, volume, mass and cost.

VI. DDRA PROOF-OF-CONCEPT PROTOTYPE

This section describes our proof-of-concept prototype. To simplify the integration, the concept illustrated in Figure 4 is slightly rearranged in Figure 5. This implementation is now asymmetric, but, if *R* is large enough, the two designs behave very similarly.

For the proof-of-concept prototype, the Harmonic Drive (HD) gearing technology was chosen. In general, a HD gearbox is composed of three components: 1) a wave generator (WG), 2) a flexible spline (FS) and 3) a circular spline (CS). The two HD gearing sets used also have a fourth component called the dynamic spline (DS) which rotates with the FS [14]. Figure 6 shows a simplified cut-off view of the dual differential mechanism. Numbers referring to the ports are added to facilitate its association with Figure 5. The prototype, realized with two commercially available MR brakes, one DC motor and the dual differential mechanism, is shown in Figure 7 and in Figure 8.

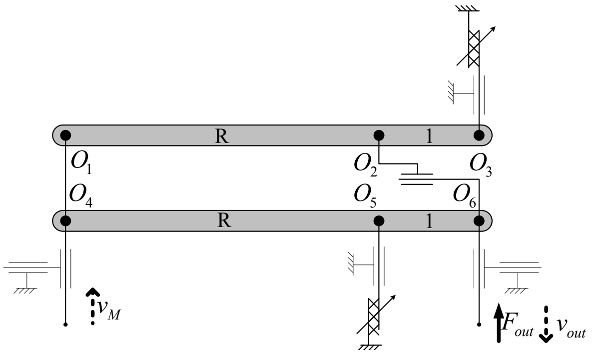

Fig. 5. DDRA concept with asymmetric configuration.

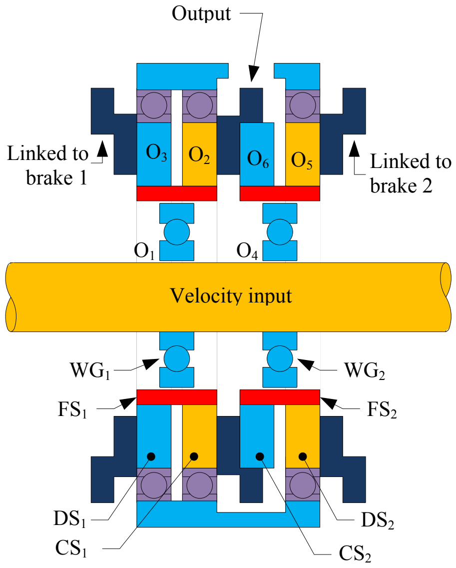

Fig. 6. Dual Differential mechanism.

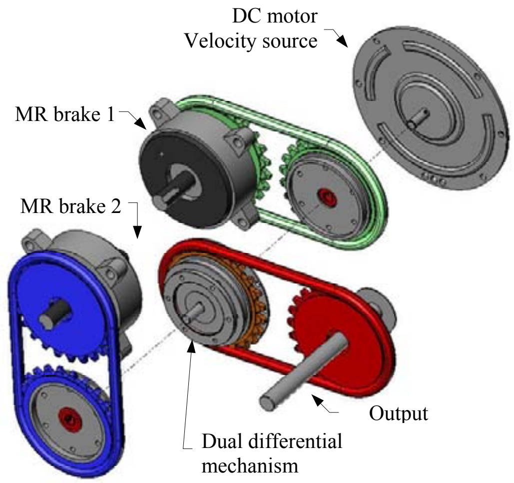

Fig. 7. DDRA prototype exploded view.

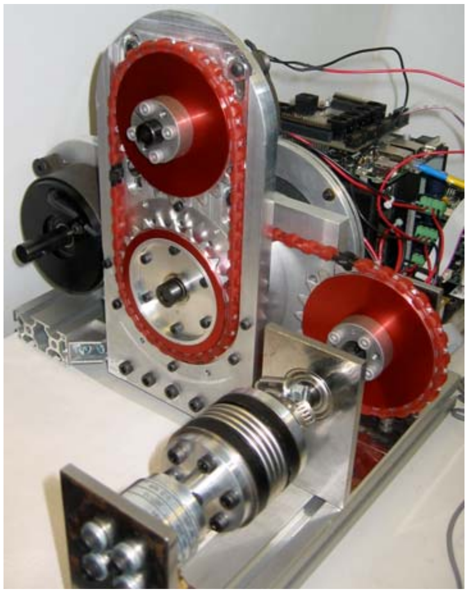

Fig. 8. DDRA prototype with torque sensor installed for characterization.

VII. RESULTS

This section shows the results obtained with an electrical tension feed-forward control scheme. In this project, force control is realized as a preliminary step towards a future implementation of impedance control, also known as interaction control, which aims at modulating the output dynamic behavior ($F_{out}(v_{out})$) to enable safe and versatile interaction.

To implement this force controller, the relationships between the output torque (T) and the electrical tension applied to brakes 1 and 2 (E_1 and E_2) were first identified. For that purpose, the motor was set to rotate at a constant velocity while a slowly varying sinusoidal tension was sent to the brakes. Output torque was measured with motion blocked. Data and fitted linear curves are presented in Figure 9. Partly because of the asymmetry of the design, the curves do not cross at exactly 0 Nm, but rather at a small torque value (0^*). Figure 10 illustrates the torque controller. Transfer function G_{th}(s) refers to the resulting force generation dynamics which is here considered linear to enable further discussion.

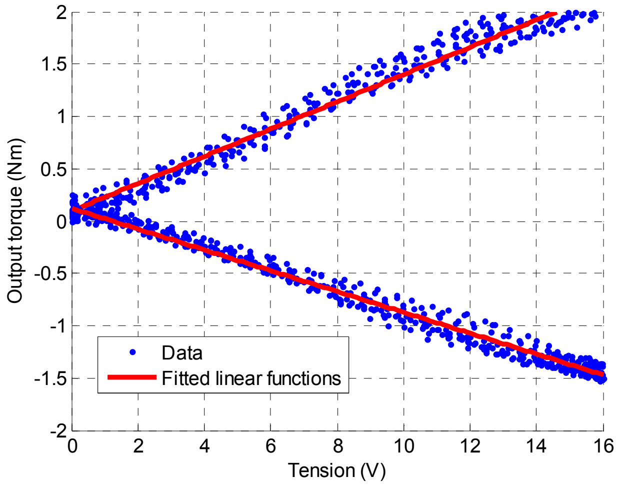

Fig. 9 Torque output function of input tension in brakes 1 and 2.

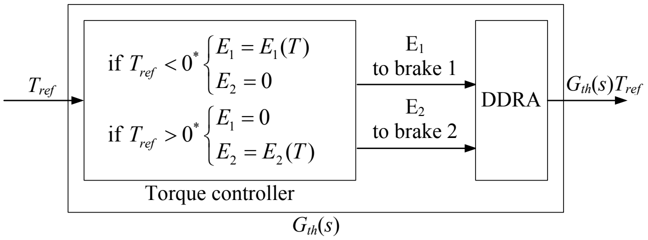

Fig. 10 Feed-forward torque control scheme

To gain more insight, Equation 3 is used. It states that the output force can be represented as a linear combination of contributions from output impedance ($Z_{out}(s)$) and input force (F_{in}) with transfer function $H_{th}(s)$ (measured with output motion blocked) [4] [5] [10]. Furthermore, if the input force responds linearly to a force command (F_{ref}), then the theorem can be formulated as in (4). This equation, which decouples the influences of the torque controller and the output velocity, is useful for performance analysis.

$$F_{out}(s) = H_{th}(s)F_{in} - Z_{out}(s)v_{out} \tag{3}$$

$$F_{out}(s) = G_{th}(s)F_{ref} - Z_{out}(s)v_{out} \tag{4}$$

To analyze the performance of the torque controller (G_{th}) with output motion blocked, Figure 11 illustrates the response to a slow sinusoidal command and to a step command. These resultsthat transfer function G_{th} is approximately a first order low pass filter with a time constant of 40 ms, equivalent to a bandwidth of 4 Hz.

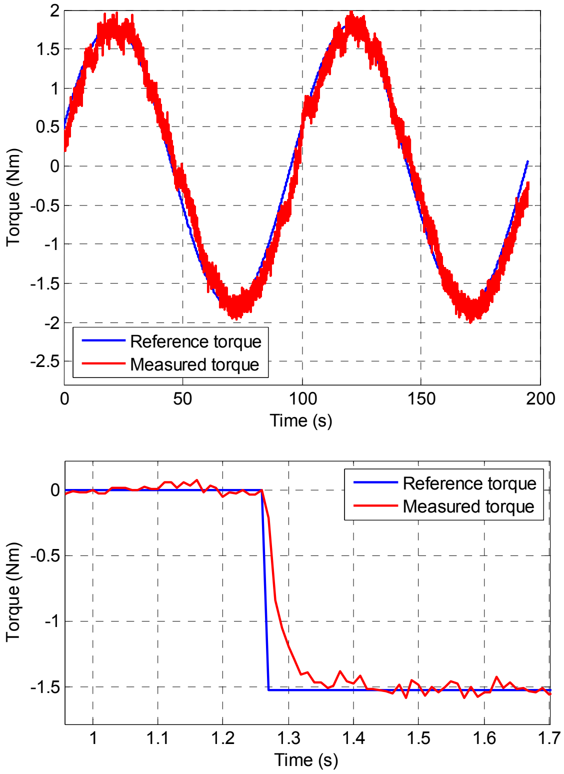

Fig. 11 Torque response to a slow sinusoidal command (up) and to a step command (down) with output motion blocked.

VIII. DISCUSSION

This prototype was realized in order to validate a proposed actuation concept. Results were judged promising and, consequently, the design of a second prototype is now under way to provide better performances in a convenient package.

In relation to the four basic characteristics for a safe and versatile actuator, our proof-of-concept prototype has the following capabilities:

1. High torque density: Torque density was not considered in this phase of the project. However, it is a goal for the second prototype that torque density be superior to one half the expected torque density of an equivalent high performance geared motor.

2. Sufficient bandwidth: the force bandwidth limit of the prototype (transfer function G_{th}) was characterized at about 4 Hz. Compared to the 7 Hz usually considered as the upper limit of human force control [10], this is not very impressive. However, solutions, including using a current feed-forward approach and MR brake optimization, are available and will be implemented in the second prototype. Using these techniques, a time constant of 5 ms (32 Hz bandwidth) could be achieved [15].
3. Very low output impedance: The output impedance Z_{out}, which is a measure of the sensibility of torque to motion, is an important metric for actuators designed for interaction. No measures are available for the proof-of-concept prototype, but an analytical estimation is possible. Z_{out} is expected to be characterized primarily by inertia, estimated at 3.3 kg cm^2, and a small damping. If the same DC motor was connected to a gearbox with the same 50:1 ratio in a classic configuration, inertia would be over 4250 $kg.cm^2$. The concept enabled a very important reduction.
4. Capability to display forces with a high-fidelity: Figure 11 shows interesting performances. However, two phenomena should be reported. The first is the presence of hysteresis in the torque generation of the MR brakes, likely caused by magnetism. The second is a substantial output force noise when the motor is running at high velocity, which is likely caused by the non homokineticity of the HD gearings interacting with the brake inertias. In the second prototype, magnetic hysteresis will be reduced by using carefully processed ferromagnetic materials and torque noise will be reduced by using homokinetic gearing technologies.

IX. CONCLUSION

This paper introduces an innovative actuation concept named Dual Differential Rheological Actuator (DDRA) with a high potential for safe and versatile robotic interactions. The built prototype validates the approach and provides key insights for the design of a future compact version. If successful, this actuation concept could represent a significant step toward the realization of complex interaction tasks.

ACKNOWLEDGMENT

A patent is pending on the DDRA under the name “Dual Differential Rheologic Actuator Fit for Interaction Tasks and Fast Motion », USA patent application #61/064.813, application date 27-03-2008.

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