A Physical Prototype of an Automotive Magnetorheological Differential

A. Lanzotti, F. Renno, M. Russo, R. Russo, M. Terzo

Abstract— **The development of an automotive semi-active differential is described. The device is based on the use of a magnetorheological fluid and allows to control the locking torque and, consequently, to improve the vehicle handling. In order to evaluate the effectiveness of the proposed device, a physical prototype was realized and the first experimental tests were carried out.**

Index Terms — **Magnetorheological fluid, automotive differential, vehicle dynamics**

I. Introduction

SEVERAL developments concerned the free differential with the aim of solving its limit: if one driving wheel travels on a low friction surface, the tyre- road interaction force is minimized and a limited torque is transmitted to the other one, with the consequence that the vehicle loses the driving stability. Suitable passive devices [1, 2] (so called limited slip differential) were realized in order to transmit torque to a wheel, even if the other one is on a slippery surface. The limited slip differentials are based on a mating between the two side gears with the effect of generating different driving torques. This differential locking effect makes the vehicle capable to move itself also in presence of a wheel characterized by low traction. The locking torque that characterizes the limited slip differentials is typically depending on the wheel relative speed or on the torque acting on the differential case and generates its effects independently from the vehicle handling, e.g. understeering/oversteering. Consequently, in some dynamic conditions, the locking torque can also determine an undesired vehicle behaviour. Thanks to the development of the electronic control, semi-active and active [3] differentials were realized: these devices are characterized by a controllable locking torque and typically employ hydraulic or electrical actuation systems to engage a clutch [4 - 6] which determines issues in terms of wear and NVH (noise, vibration and harshness) due to the sliding between the parts that are in contact.

This paper focuses on a controllable limited slip differential which advantage consists of the employment of a contactless clutch that is activated by means of the magnetisation of a magnetorheological (MR) fluid and, consequently, no hydraulic pump or electric motor are requested. MR fluid are extensively employed in brake, clutch and damper [7 - 9], but no examples concerning the design and the development of MR fluid based automotive differential are available in the scientific literature.

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A physical prototype was realized and tested in order to verify its locking effect. The experimental results highlight the functionality of the proposed magnetorheological fluid limited slip differential (MRF LSD).

II. The Magnetorheological Fluid Limited Slip Differential

Magnetorheological fluids are suspensions of micron-sized and magnetisable particles in a carrier fluid. Normally, MR fluids are free-flowing liquids, having a consistency similar to that of lubricant oil. However, when a magnetic field is applied, their rehology changes to more a solid-like gel. MR fluid rehology is modelled in pre-yield and post-yield regimes. In the pre-yield regime, MR fluids demonstrate a visco-elastic behaviour. For visco-elastic materials, while some of the applied energy is recovered (elastic behaviour), some is dissipated in the form of heat. The visco-elastic behaviour of the MR fluids in the pre-yield regime is analyzed by linear visco-elastic theories. On the other hand, the MR fluid post-yield behaviour, in presence of a magnetic field, is approximated by the Bingham plastic model [10]:

$$\tau = \tau_{yd}(H) + \eta \frac{d\gamma}{dt} \quad (1)$$

where, τ is the shear stress, τ_{yd} is the dynamic yield stress due to applied magnetic field (H), η is the no- field fluid viscosity, and $d\gamma/dt$ is the shear rate. When the magnetic field intensity rises, the ferromagnetic particles find an orientation and the yield stress increases. This property makes the MR fluids functional for the employment in controllable devices [11 – 14].

Fig. 1 illustrates the MRF LSD logical scheme. It consists of a conventional part and an unconventional one. The side gears (A and B), the planetary gears (G), the differential case (P) and the differential gear (R) characterize the conventional part of the MRF LSD. The unconventional part is constituted by a disk housing (C) and a coil (S). The disk housing engages the side gear A and the differential case P, and contains facing plates, alternately integral with the side gear and the differential case P, that perform the friction surfaces. Suitable spacer elements create a gap in which the MR fluid is contained.

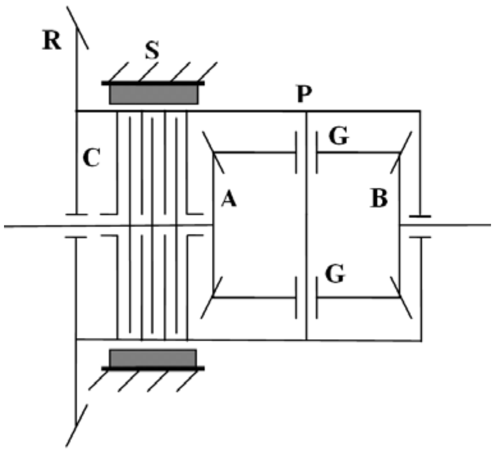

Fig. 1. Logical scheme of the MRF LSD

The device is able to transfer the power on the driving wheels and, changing the coil current, it is possible to bias the torque with different ratio. While in a passive limited slip differential the locking torque depends on relative sliding or on the torque acting on differential case, in the MRF LSD it depends on the magnetic field essentially.

Taking the Willis ratio ε_0 into account, it can be written:

$$\varepsilon_0 = \frac{\omega_A - \omega_P}{\omega_B - \omega_P} = -1 \tag{2}$$

where ω_A and ω_B are rotational speed of the side gear A and B respectively, and ω_P is the rotational speed of the differential case.

From (2) it can be observed that the rotational speed of the differential case is the average of the speed of the side gears:

$$\omega_P = \frac{\omega_A + \omega_B}{2} \tag{3}$$

By means of the rotational equilibrium equation, energy balance and (3), the expression of the output torque T_A and T_B can be determined. In steady-state conditions, being T_P the torque acting on the differential case and W_l the power due to the locking torque T_l acting between the differential case P and the side gear A, it can be written:

$$\begin{cases} T_P - T_A - T_B = 0 \\ T_P\omega_P - T_A\omega_A - T_B\omega_B - W_l = 0 \\ \omega_P = \dfrac{\omega_A + \omega_B}{2} \end{cases} \tag{4}$$

The torque T_A and T_B can be expressed as:

$$\begin{cases} T_A = \dfrac{T_P}{2} - \dfrac{W_l}{\omega_A - \omega_B} \\ T_B = \dfrac{T_P}{2} + \dfrac{W_l}{\omega_A - \omega_B} \end{cases} \tag{5}$$

The power W_l, adopting the convention of positive T_l, is given by:

$$W_l = T_l \left|\omega_A - \omega_P\right| \tag{6}$$

Consequently:

$$\begin{cases} T_A = \dfrac{T_P}{2} - \dfrac{T_l}{2} \\ T_B = \dfrac{T_P}{2} + \dfrac{T_l}{2} \end{cases} \text{if } \omega_A > \omega_P > \omega_B \tag{7}$$

$$\begin{cases} T_A = \dfrac{T_P}{2} + \dfrac{T_l}{2} \\ T_B = \dfrac{T_P}{2} - \dfrac{T_l}{2} \end{cases} \text{if } \omega_A < \omega_P < \omega_B \tag{8}$$

By means of a suitable control system, the locking torque T_l can be adjusted in order to enhance the vehicle dynamic behaviour [15]. The device is a semi-active one since it is able to regulate the locking torque value while the torque flux direction is only established by the wheel kinematics: the supplied energy determines a controllable torque flux from the fastest side gear to the slowest one in order to lock the differential in a wide range of operating conditions.

The differential locking torque is given by the following contributions: the torque due to friction (T_f), e.g. of the seals and gear, the torque due to the magnetic field (T_M) and the torque due to the fluid viscosity (T_V). Therefore, it follows:

$$T_l = T_f + T_M + T_V \tag{9}$$

Taking into account (1), the magnetic and the viscous contributions are given by:

$$T_M + T_V = 2\pi n \int_{r_i}^{r_o} \tau(r) r^2 dr \tag{10}$$

in which n is the number of friction surfaces, r_i and r_o are, respectively, the inner and the outer radius of the friction surface and r the generic radius. Consequently:

$$T_M = \frac{2}{3}\pi n \tau_y(H)\left(r_o^{\,3} - r_i^{\,3}\right) \tag{11}$$

$$T_V = \frac{\pi n \eta \left|\omega_A - \omega_P\right|}{2d}\left(r_o^{\,4} - r_i^{\,4}\right) \tag{12}$$

where d is the gap between the several disks.

The no-field viscosity of the MR fluid typically allows to consider the viscous contribution negligible respect to the magnetic one. This characteristic makes the MRF LSD with non-magnetized fluid very close to a free differential, with the relevant advantage of reducing the energy loss and the undesired torque apportionment. Consequently, the driving

ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

torque can be split in a controlled manner only when it generates a vehicle dynamics improvement.

The virtual prototype of the MRF LSD cross section is illustrated in Fig. 2 and the several components are listed in Table 1. Among the listed components, the coil and its housing only are motionless respect to the gear box in order to avoid travelling electrical contacts.

The differential gear was designed (n° 5 in Fig. 2) in order to contain the unconventional part, constituted by the disk housing and the coil.

As regards the conventional part of the MRF LSD, it is based on the morphology and dimensions of the common open differential that equipped a middle class vehicle.

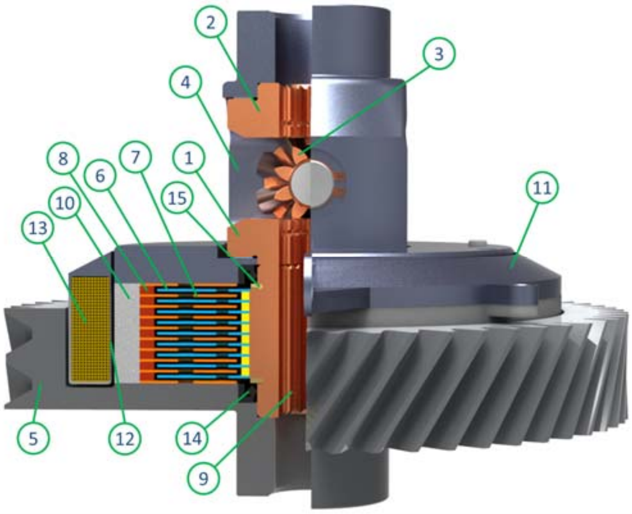

Fig. 2. MRF LSD cross section

TABLE I
COMPONENTS OF THE MRF LSD

No	Description	Material
1	Side gear A	Standard steel
2	Side gear B	Standard steel
3	Planetary gear	Standard steel
4	Differential case P	Low carbon steel (AISI 1008)
5	Differential gear	Low carbon steel (AISI 1008)
6	Inner disk	Low carbon steel (AISI 1008)
7	Outer disk	Low carbon steel (AISI 1008)
8	Spacer elements	Austenitic stainless steel (AISI 304)
9	Disk shaft	Austenitic stainless steel (AISI 304)
10	Disk housing	Austenitic stainless steel (AISI 304)
11	Coil outer housing	Low carbon steel (AISI 1008)
12	Coil inner housing	Austenitic stainless steel (AISI 304)
13	Coil	Copper
14	Sealing	Steel
15	Sealing	Steel

As an example, Fig. 4 shows a first physical prototype of the MRF LSD. The differential gear was not completely refined since this feature was not necessary for the testing procedure that will be described after.

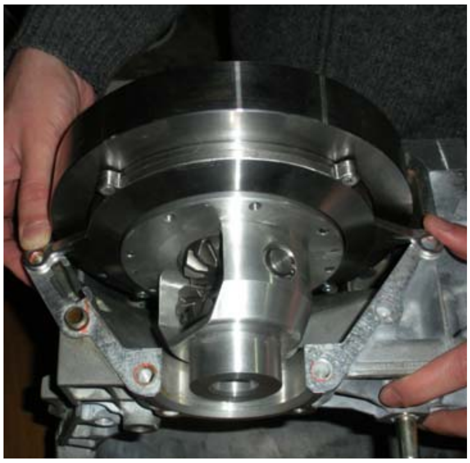

Fig. 3. Physical prototype of the MRF LSD

III. Experimental Evaluation

A test rig (Fig. 4) was set up in order to carry out the experimental investigations.

It includes the MRF LSD, an inverter driven AC motor and a reduction unit. Suitable couplings were adopted to link the several components.

The measured quantities are:

- rotational speed of the AC motor by phonic wheel and proximity pick up
- input current to the MRF LSD by Hall effect closed loop current sensor
- transmitted torque by high stiffness strain gauge load cell.

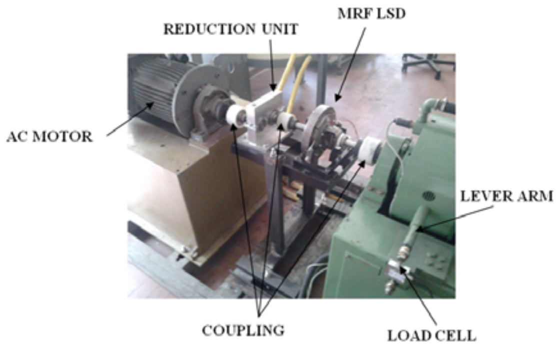

Fig. 4. MRF LSD cross section

Current input was provided by an adjustable 3kW DC power supply. All measured quantities were acquired and stored by National Instruments Corporation board and software (LabVIEW ©).

The experimental test rig allows to measure the locking torque T_l : with reference to Fig. 5, suitable bearings (A) sustain the differential case that was made integral with the load cell by means of the shaft (B) and the lever arm indicated in Fig. 4. In this way, the locking torque is transmitted to the differential case, by means of the magnetic and the viscous effects, and its value is measured by the load cell. The coil housing (C) was made fixed on a frame.

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ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

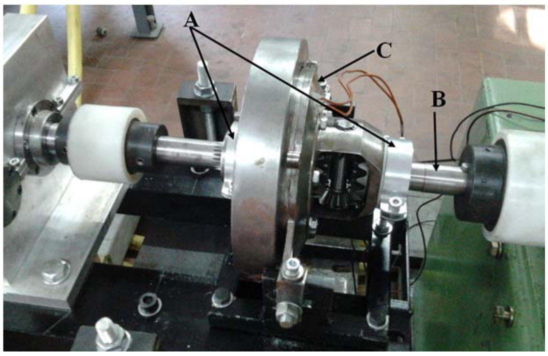

Fig. 5. Test rig details

In order to evaluate the effectiveness of the manufactured MRF LSD, first results concerning static and dynamic properties are presented. The tests were conducted at a relative rotational velocity ω_A of 25 rpm. This constitutes a high value reachable in handling manoeuvres and consequently was functional to evaluate the viscous contribution on the locking torque. Fig. 6 illustrates the static torque-current curve. It can be observed that the MRF LSD is characterized by a limited zero current torque ($T_f + T_V$) that makes the device similar to a common free differential. This allows to avoid not requested locking effects and undesirable vehicle dynamic behaviours [15]. At the same time, the MRF LSD exhibits a significant locking torque in presence of a reduced supply current and shows a substantially linear tendency that allows an easier feedback controller design procedure.

The magnetic torque can be obtained subtracting the zero current torque from the total one: in this way a T_M/i gain of 6.8 Nm/A was estimated.

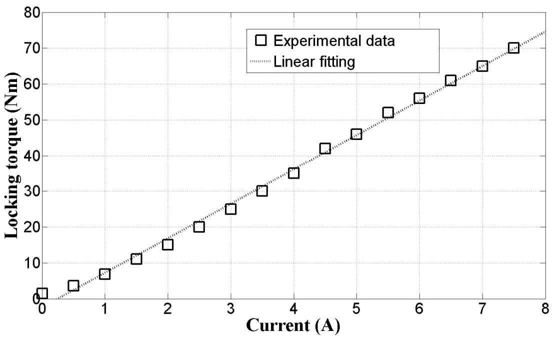

Fig. 6. Locking torque vs supply current

The transient response of the device was obtained adopting as input an up-step down-step sequence in terms of supply current with an amplitude of 7 A. In any case, the linear behaviour allows to consider the dynamic properties of the MRF LSD independent from the current input. Fig. 7 shows the output torque of the MRF LSD normalized by the respective maximum value. The input-output relationship can be well approximated by a first order linear time-invariant system and consequently a time constant of 0.03 s was determined, satisfying the typical dynamic requirements of the vehicle handling control systems.

A complete demagnetization is obtained after the down-step, allowing to prevent a residual activation of the device and, furthermore, the requested electrical power is fully compatible with the peak values of the modern automotive alternators [16].

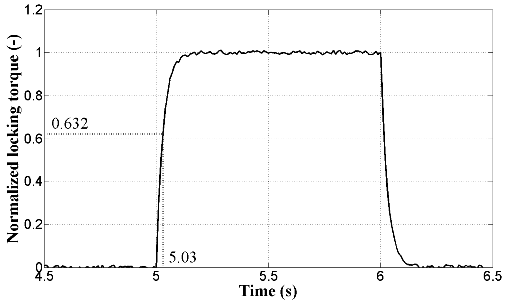

Fig. 7. Step response of the MRF LSD

IV. Conclusion

A magnetorheological semi-active differential was described and a first physical prototype was illustrated and tested. The experimental results highlight the static and the dynamic performances of the MRF LSD, showing its inclination to be a useful tool to control yaw moment and, consequently, to improve vehicle handling.

References

[1] I.H. Taureg, J. Horst, "Induced torque amplification in viscous couplings", *SAE Paper 900557*, 1990.

[2] T. Gassmann, J. Barlage, "Visco-Lok: a speed-sensing limited-slip device with high torque progressive engagement", *SAE Paper 960718*, 1996.

[3] M. Canale, L. Fagiano, M. Milanese, P. Borodani, "Robust vehicle yaw control using an active differential and IMC techniques", *Control Engineering Practice*, vol. 15, no. 18, pp. 923 – 941, 2007.

[4] G. Naito, E. Yaguchi, T. Matuda, M. Asahi, T. Nakata, I. Inokuchi, "New electronically controlled torque split 4WD system for improving cornering performance", *SAE Paper 900556*, 1990.

[5] M. Teraoka, "Development of the electro-magnetic controlled limited slip differential unit (EMCD)", *SAE Paper 931023*, 1993.

[6] J. Asgari, D. Hrovat, "On-demand four wheel-drive transfer case modeling", *SAE Paper 970969*, 1997.

[7] K. Karakoc, E.J. Park, A. Suleman, "Design considerations for an automotive magnetorheological brake", *Mechatronics*, vol. 18, no. 8, pp. 434-447, 2008.

[8] B. Kavlicoglu, N. Kavlicoglu, Y. Liu, C. Evrensel, A. Fuchs, Korol G and F. Gordaninejad, "Response time and performance of a high-torque magneto-rheological fluid limited slip differential clutch", *Smart Materials and Structures*, vol. 16, pp. 149-159, 2007.

[9] G.Z. Yao, F.F. Yap, G. Chen, W.H. Li, S.H. Yeo, "MR damper and its application for semi-active control of vehicle suspension system", *Mechatronics*, vol. 12, no. 7, pp. 963 – 973, 2002.

[10] J. An, D.S. Kwon, "Modeling of a magnetorheological actuator including magnetic hysteresis", *J Intel Mater Syst Struct*, vol. 14, no. 9, pp. 541–550, 2003.

[11] E.J. Park, D. Stoikov, L. Falcao da Luz, A. Suleman, "A performance evaluation of an automotive magnetorheological brake design with a sliding mode controller", *Mechatronics*, vol. 16, no. 7, pp. 405 – 416, 2006.

[12] R. Russo, M. Terzo, "Modelling, parameter identification, and control of a shear mode magnetorheological device", in *Proc IMechE Part I: Journal of Systems and Control Engineering*, vol. 225, no. 5, pp. 549–562, 2011.

[13] R. Russo, M. Terzo, "Design of an adaptive control for a magnetorheological fluid brake with model parameters depending on temperature and speed", *Smart Materials and Structures*, vol. 20, no. 11, 115003 (9pp), 2011.

[14] R. Russo, M. Terzo, F. Timpone, "Software-in-the-loop development and experimental testing of a semi-active magnetorheological coupling for 4WD on demand vehicles", in *Proc. of the Mini Conference on Vehicle System Dynamics, Identification and Anomalies*, pp. 73 – 82, 2008.

[15] R. De Rosa, M. Russo, R. Russo, M. Terzo, "Optimisation of handling and traction in a rear wheel drive vehicle by means of magneto-

rheological semi-active differential", *Vehicle System Dynamics*, vol. 47, no. 5, pp. 533 – 550, 2009.

[16] D.J. Perreault, V. Caliskan, "Automotive power generation and control", *IEEE Transactions on Power Generation and Control*, vol. 19, no. 3, pp. 618 – 630, 2004.

ISBN: 978-988-19252-9-9
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)