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Design and development of an automotive magnetorheological semi-active differential

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ABSTRACT

This paper describes a research activity concerning the design and the development of an automotive semi-active differential based on the use of a magnetorheological fluid that allows to control the locking torque and, consequently, to improve the vehicle handling. Starting from a gearbox of a common front wheel drive vehicle, the boundary volume of the new device was defined by means of reverse engineering techniques. Two alternative architectures were proposed and compared to select the best one in terms of functionality. Then, the selected functional scheme was modeled and optimized by means of multiphysics simulations. The definition of a reiterative process, based on the use of a specific cost function, allowed to optimize the design variables and to obtain the final virtual prototype. In order to evaluate the effectiveness of the proposed device, a physical prototype was realized. First experimental tests were carried out validating the design process.

1. Introduction

The vehicle drive-line is commonly constituted by the gearbox, coupled with the engine by means of a clutch and differential(s). The need to transmit the torque to the driving wheels and, at the same time, the demand of making the wheels free to rotate at different speed, make the differential very functional for the purpose. The commonly employed differential (so called free or open differential) receives the torque from the gearbox and splits it in two equal parts that act on the driving wheels. Consequently, neglecting the internal friction loss, the driving wheels are subjected to the same driving torque and can rotate at different speed in accordance with the vehicle kinematics. Several developments concerned the free differential with the aim of solving its limit: if one driving wheel travels on a low friction surface, the tire–road interaction force is minimized and a limited torque is transmitted to the other one with the consequence that the vehicle is not able to start. Suitable passive devices [1,2] (so called limited slip differential) were realized in order to transmit the torque to a wheel even if the other one is on a slippery surface. The limited slip differentials depend on the 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 depends typically 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 behavior. 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 whose advantage consists of the employment of a contactless clutch that is activated by means of the magnetization 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. Two main objectives are pursued and described in the paper:

(1) The design and the development of an innovative semi-active device that transfers and biases the torque between the two half-shafts by means of the magnetization of a magnetorheological (MR) fluid.

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(2) The respect of the constraints due to the most critical potential use of the device in a front wheel drive vehicle.

The design of the magnetorheological fluid limited slip differential (MRF LSD) was carried out with the constraints due to the available space that in origin was occupied by a passive device (free differential) located in the gearbox of a common front wheel drive (FWD) vehicle: this represents a strict design challenge caused by the chosen power train layout.

A Reverse Engineering (RE) process, based on 3D laser scanner measurements, was adopted to determine the boundary volume and to define the maximum external sizes of the MRF LSD. After selecting the suitable MRF LSD architecture, a virtual prototype was realized and then, by means of an optimization procedure based on a multiphysics approach, the design variables were determined and the final CAD model was obtained. The successive manufacturing and assembling phases allowed to realize the physical prototype that was successively tested in order to verify its locking effect. The experimental results highlight the functionality of the MRF LSD and validate the design procedure.

The paper is organized as follows: Section 2 describes the MRF LSD, Section 3 describes the virtual prototyping techniques while the main design criteria and the optimization process are discussed in Section 4. The test rig is described in Section 5 and the experimental results are illustrated in Section 6.

2. Magnetorheological fluid limited slip differential

2.1. Magnetorheological fluids

Magnetorheological (MR) 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 a more solid-like gel. MR fluid rehology is modeled in pre-yield and post-yield regimes. In the pre-yield regime, MR fluids demonstrate a visco-elastic behavior. For visco-elastic materials, while some of the applied energy is recovered (elastic behavior), some is dissipated in the form of heat. The visco-elastic behavior 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 behavior in presence of a magnetic field is approximated by the Bingham plastic model [10]:

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

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 [11–13].

2.2. The MRF LSD

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 consists of 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.

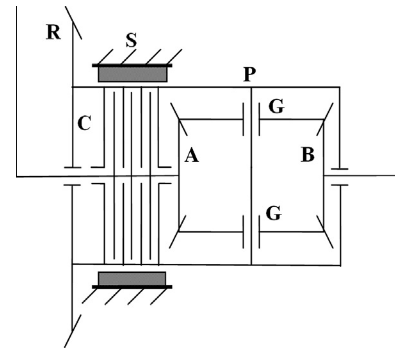

Fig. 1. Logical scheme of the MRF LSD.

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 the relative sliding or on the torque acting on differential case, in the MRF LSD it depends on the magnetic field essentially and the device can be locked in a controlled manner to enhance the vehicle dynamic behavior [14–16].

The differential locking torque is given by the following contributions: the torque due to the 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:

$$T_l = T_f + T_M + T_V \tag{2}$$

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

$$T_M + T_V = 2\pi n \int_{r_i}^{r_o} \tau(r) r^2 dr \tag{3}$$

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:

$$T_M = \frac{2}{3}\pi n \tau_y(H)(r_o^3 - r_i^3) \tag{4}$$

$$T_V = \frac{\pi n \eta |\omega_A - \omega_P|}{2d}(r_o^4 - r_i^4) \tag{5}$$

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

3. Design of the MRF LSD by means of the virtual prototyping techniques

The procedure adopted to generate the MRF LSD virtual prototype started with the concept generation phase and the definition of the architecture of the device. In fact, a different and uncommon displacement of the main parts of the differential and the use of the MR fluid can represent an innovative way to control and to improve its performances and no hydraulic pump or electric motor are needed. Then, by means of the reverse engineering techniques, the strict geometrical constraints, imposed by the shape and the internal dimensions of the gearbox of a common front wheel drive vehicle equipped with a free differential, were considered. This caused a double challenging aspect: firstly, the driveline of a