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Enhancement of vehicle dynamics via an innovative magnetorheological fluid limited slip differential

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ABSTRACT

A new automotive controllable differential is proposed and tested, firstly in software environment and, successively, following a hardware in the loop procedure based on the employment of the physical prototype. The device is based on the employment of magnetorheological fluid, whose magnetization allows to generate the locking torque and, consequently, the corrective yaw moment. A vehicle model has been derived and adopted for the design of a yaw moment controller based on the sliding mode approach. Some feedbacks requested by the controller have been estimated by means of an extended Kalman filter. The obtained results show the effectiveness of the device in terms of vehicle dynamics improvement. Indeed, the results reached by the vehicle in presence of the new differential confirm the improved performances for both steady and unsteady state manoeuvres. Moreover, the hardware in the loop testing allows to overcome the limits due to the modelling of the differential, fully validating the physical prototype.

1. Introduction

In the recent years the research in the automotive field is consistently focused on the active control systems of the vehicle dynamics. The more known systems are employed to control the vehicle braking [1,2] and to prevent unstable behaviour [3,4]. The systems that belong to the last category are generically indicated as yaw moment control systems and are adopted in order to enhance the handling and to prevent unstable behaviours. They can be substantially divided in three sub-categories: systems based on differential braking, systems based on the controlled torque distribution, and steer by wire systems [5]. With reference to the torque distribution systems, they are substantially characterized by limited slip differentials (LSDs) able to generate an internal locking torque that allows to differentiate the output torque and to generate a corrective yaw moment on the vehicle. The presence of an internal locking torque makes the LSDs different from the more common open differentials, in which the torque on the two side gears are the same in every condition. Moreover, differently from a passive LSD, a controllable one is able to generate the internal locking effect, and consequently a torque distribution, only when it generates an improvement in vehicle handling and, so, undesired dynamic behaviours are not produced [6–8]. The present paper focuses on a torque distribution system based on a new controllable automotive LSD [9,10] that employs magnetorheological fluid to generate the internal locking torque: in this way an asymmetric distribution of the driving torque is realized and a yaw moment control produced.

The magnetorheological (MR) fluids consist of suspensions of micron-sized ferrous particles immersed in a carrier fluid; their rheological behaviour can be changed by means of an applied magnetic field. Researchers have used the controllable

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variation in yield stress to develop various smart devices such as vibration dampers, transmission clutches and brakes [11–17], but no examples concerning the design and the development of MR fluid based automotive differential are available in the scientific literature. As it will be better detailed in the text, the new magnetorheological fluid limited slip differential (MRF LSD) can be classified as a semi-active device and, in this category, it is characterized by the fundamental advantage of not requiring invasive additional actuation systems (e.g. hydraulic circuit) to engage the internal parts for the generation of the locking torque. Additionally, the absence of sliding parts in contact, that are typical for the semi-active multi-plate clutch limited slip differentials [18], reduces the stick-slip and the wear phenomenon. As concerns the dynamic performances, it can be observed that the transient properties of the MR fluids make the device a functional system for the yaw moment control [10].

Software simulations and hardware in the loop testing of the MRF LSD are presented in this paper in order to evaluate the benefits reachable by means of the proposed device. Software in the loop simulations have been carried out through a mathematical model of the MRF LSD equipped vehicle. To this aim, a control algorithm and an extended Kalman filter have been designed to generate the control action for the MRF LSD. Moreover, the presented hardware in the loop results is useful to evaluate the performances of the physical MRF LSD integrated with the simulated vehicle and controlled by means of the suitable algorithm.

The paper is organized as follows: a description of the proposed device is given in Section 2 and a mathematical model of the MRF LSD equipped vehicle is described in Section 3. The controller design, together with an extended Kalman filter synthesis, is detailed in Section 4. The software simulations and the hardware in the loop results are presented in Sections 5 and 6 respectively. In the last section, some comments and statements are drawn.

2. The magnetorheological fluid limited slip differential

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 constitute the friction surfaces. Suitable spacer elements create a gap filled with the MR fluid.

The shear stress in the MR fluid gives rise to a locking torque T_l acting between the differential case P and the side gear A. The device is able to transfer the power on the driving wheels and, changing the coil current (i.e. the shear stress in the MR fluid), it is possible to bias the torque with different ratio. Moreover, in absence of coil current, thanks to the very low MR fluid viscosity, the T_l torque is practically null, making the MRF LSD with no-magnetized fluid very close to an open differential [10].

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.

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

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

where ω_A and ω_B are the angular velocities of the side gears A and B respectively (equal to the ones of the driving wheels), and ω_P is the angular velocity of the differential case.

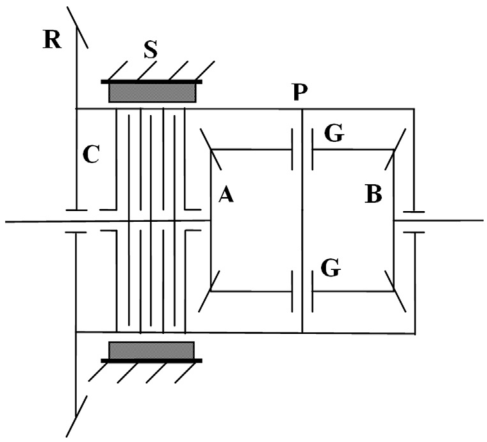

Fig. 1. Logical scheme of the MRF LSD.