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MR fluid viscous coupling and its torque delivery control

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Abstract

A torque controllable viscous coupling is presented. The coupling consists of two types of discs with slits. One is connected to a housing (follower discs) and the other is connected to a shaft (driving discs). The driving discs and follower discs are arranged by turns and they are sandwiched. MR fluid is filled in the housing. Magnetic fields freeze the fluid, so that the shear torque is generated between the diving discs and follower discs due to shears between the slits in the discs under the magnetic fields. The torque is controlled by electromagnets. In order to have large torque with small electric power, coil turns have to be large, so that response delays due to inductance of the coil. A controller which improves response is presented. A method of control is presented which controls distribution of torque of rear wheel and front wheel.

Keywords: MR fluid; Viscous coupling; Torque control; Electromagnet

1. Introduction

It is necessary to deliver the engine torques to front and rear wheels automatically for four-wheel drive automobiles. There are some systems for the automatic torque deliver system. The most popular system is the viscous coupling [1,2] made of multi-disc type coupling in which silicon oil is the driving fluid. The torque of the coupling is in proportion to the differential velocity between the front and real wheels. The appropriate torque delivery is desirable to have stable driving of the four-wheel drive automobile, and to have good energy efficiency. In the viscous coupling, however, the torque cannot be controlled, so that the appropriate torque delivery cannot be performed. The active control type coupling is desirable for the torque delivery system, and an electromagnetic friction-disc-type coupling was developed. In the coupling, however, it is difficult to perform precise control because the friction torque among discs is unstable, and connection of torque is not continuously. In addition, there is disc friction noise.

From this situation, the present article provides a new type noiseless MR fluid coupling, in which the torque is controlled continuously.

2. Analysis of the transmission torque

2.1. Friction torque between discs

Consider a three layered sandwich structure of fixed disc, rotation disc, and fixed disc which lie between N- and S-pole of the magnets. When the magnetorheological fluid is filled in the gaps, the friction torque due to a small radius dr at the radius r is $\mathrm{d}T'_f = 2\pi r\,\mathrm{d}r f_f r$. Hence, the torque T'_f is

$$T'_f = 2\pi f_f \int_a^R r^2\,\mathrm{d}r = \frac{2}{3}\pi f_f (R^3 - a^3), \tag{1}$$

where a is the inner radius of the disc, R is the outer radius of the disc, f_f is the friction stress between discs without slits, under the magnetic fields. Since there are two friction surfaces for a rotation disc, we have $T_f = 2T'_f$. Consider a

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reference disc whose inner radius is a_0, outer radius is R_0, friction stress is f_{f0}, and friction torque is T_{f0}. From Eq. (1), we have

$$f_{f0} = \frac{3T_{f0}}{4\pi(R_0^3 - a_0^3)}.$$

Magnetic fluxes concentrate to the Fe-plate, and so the magnetic flux density is in proportion to the inverse of surface area of the Fe-plate when there is a Fe-plate between N- and S-poles of the magnets. Hence, the friction stress f_f (N/m^2) between discs is a function of the area of the friction discs:

$$f_f(R) = \left(\frac{R_0^2 - a_0^2}{R^2 - a^2}\right)\frac{3T_{f0}}{4\pi(R_0^3 - a_0^3)}. \tag{2}$$

Eq. (2) illustrates the friction stress due to the magnetorheological fluid under magnetic fields.

The friction stress without magnetic field is

$$f_v = \frac{3T_{v0}}{4\pi(R_0^3 - a_0^3)}, \tag{3}$$

where T_{v0} is the friction torque when there is no magnetic field. Eq. (3) denotes the friction due to the viscosity of the MR fluid under non-magnetic field, so that it has constant value, which has no dependence on the radius of the disc. Hence, the friction stress due to the magnetic fields only ($f_{\mathrm{m}} = f_f - f_v$) for the disc with radii a and R is

$$f_{\mathrm{m}} = \frac{3}{4\pi(R_0^3 - a_0^3)}\left\{\left(\frac{R_0^2 - a_0^2}{R^2 - a^2}\right)T_{f_0} - T_{v_0}\right\}. \tag{4}$$

2.2. Effects of slits

When there are slits in both fixed and rotation discs, the shear stress is large because the MR fluid in the slit is frozen under magnetic fields. If the slits lie in the radial direction as shown in Fig. 1, the torque due to the shear is $T_c = \int_c^{c+l} f_c r\,\mathrm{d}r$, where $f_c(B)$ (N/m) is the shear force per unit length. Then the shear torque for the disc with n-slits is

$$T_c = \frac{\{(c+l)^2 - c^2\}n}{2} f_c, \tag{5}$$

where c is the length from the center of the disc to the inner end of the slit, l is the slit length and n is the number of slits (see Fig. 1).

The friction area decreases when there are slits. The effects on the torque is

$$T_f'' = (c + l/2)blf_f n.$$

Then the total torque is $T_1 = 2T_f' - 2T_f'' + T_c$:

$$T_1 = 2(f_{\mathrm{m}} + f_v)\{(2\pi/3)(R^3 - a^3) - (c + l/2)bln\} + \frac{\{(c+l)^2 - c^2\}n}{2}(f_{c0} + f_{\mathrm{cm}}), \tag{6}$$

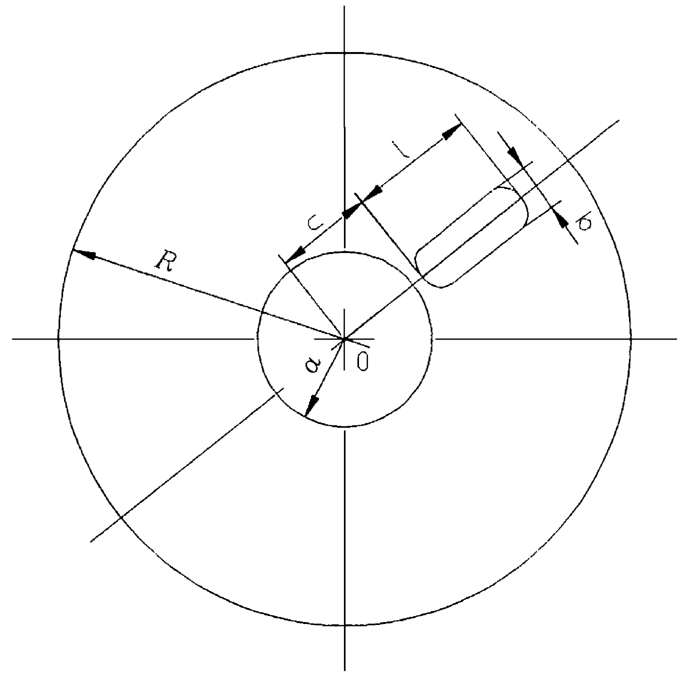

Fig. 1. Geometry of the friction disc with slits.

from which, we have

$$f_c = f_{c0} + f_{\mathrm{cm}} = \frac{2[T_1 - 2f_f\{(2\pi/3)(R^3 - a^3) - (c + l/2)bln\}]}{\{(c+l)^2 - c^2\}n}. \tag{7a}$$

Let the subscript 0 be the value for the reference disc. The shear force f_{c0} per a unit length for the reference disc, with parameters a_0, R_0, c_0, and l_0 under non-magnetic field ($B = 0$) is obtained from Eq. (7a):

$$f_{c0} = \frac{2[T_{10} - 2f_v\{(2\pi/3)(R_0^3 - a_0^3) - (c_0 + l_0/2)bl_0 n\}]}{\{(c_0 + l_0)^2 - c_0^2\}n}, \tag{7b}$$

where f_{c0} is constant which has no dependence on the slit length.

The shear stress $f_{\mathrm{cm}0}$ per unit length along the slit for the reference disc under magnetic field ($B \neq 0$) is

$$f_{\mathrm{cm}0} = \frac{2[T_1 - 2(f_{\mathrm{m}0} + f_v)\{(2\pi/3)(R_0^3 - a_0^3) - (c_0 + l_0/2)bl_0 n\}]}{\{(c_0 + l)^2 - c_0^2\}n} - f_{c0}. \tag{7c}$$

Then the shear force for the disc with inner radius a and outer radius R due to the magnetic field is

$$f_{\mathrm{cm}} = f_{\mathrm{cm}0}\left(\frac{R_0^2 - a_0^2}{R^2 - a^2}\right). \tag{7d}$$

In the calculation of the torque, a fundamental experiment has to be performed for the reference discs. The torques for the reference disc with a_0 and R_0 without slits are first measured for zero-magnetic field and the reference