

Vibration Torque Interception using Multi-Functional Electromagnetic Coupling in a HEV Drive Line

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ABSTRACT

In the present paper, we introduce a drivetrain system using an electromagnetic coupling for hybrid electric vehicles, and propose a new control concept of vibration torque interception. The electromagnetic coupling is an electric machine that is composed of a pair of rotors, and electromagnetic torque acts mutually between the rotors. In the drivetrain system, the electromagnetic coupling works as a torque transmission device with a rotational-speed-converting function. We demonstrate that, by using this control, the electromagnetic coupling also works as a damping device that intercepts the vibration torque of the internal combustion engine, while transmitting the smooth torque to its drive line. Using a model of a two-inertia resonance system, a control system is designed such that a transfer function representing input-to-output torque is shaped in the frequency domain. Experimental results obtained using an electromagnetic coupling demonstrate the effectiveness of the proposed concept.

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INTRODUCTION

An electromagnetic coupling (EMC) is an electric machine having a pair of rotors, which enables contactless torque transmission using the electromagnetic force between the input and output rotors. In addition, while transmitting mechanical power from the input to the output, the EMC generates electricity or is driven by electricity in proportion to the relative speed of the rotors. Consequently, the EMC is basically a torque-transmitting device that operates in conjunction with a power splitter. Figures 1 and 2 show the structure and function of the EMC, respectively. As can be expected from its multifunctionality, the EMC can be a key component in various kinds of drivetrain systems for hybrid electric vehicles.

A compound structure electric machine in which the double-rotor structure of the EMC is incorporated has been investigated in previous studies. The electromagnetic field coupling of the compound structure motor was analyzed in [1-5]. Moreover, the torque characteristics of the EMC and another traction motor having a compound structure were investigated. In addition, the system characteristics of the compound structure motor, which was used as the transmission of a hybrid electric vehicle, have also been investigated [6,7]. The main focuses of these studies were the characteristics of the compound structure motor as a continuously variable transmission, which is sometimes referred to as an electrically variable transmission. The performance of vehicles using such a compound structure motor has also been investigated. In a

paper submitted to SAE 2016 [8], the system efficiency of a compound structure motor was investigated by analysis and experiments using a prototype.

The advantages of the EMC originate from its contactless torque transmitting characteristics. Owing to its contactless structure, the transmitted torque can be made smooth, regardless of whether the input torque contains fluctuations, because the output torque is generated by the EMC. This means that it is possible to control the EMC such that the torque fluctuation in an internal combustion engine (ICE) can be suppressed to transfer the drive line during ICE driving conditions. In other hybrid systems, such as power split systems that use a planetary gear [9], the presence of a mechanical path from the ICE to the drive shaft causes noise and vibration issues, such as engine start/stop vibration and drone noise as well as vibration at low engine speed.

In the present paper, we consider the issues of noise and vibration suppression by controlling the EMC under ICE driving conditions. The EMC also works as a damping device that intercepts the vibration torque of the ICE, while transmitting smooth torque to its drive line. Using a model of a two-inertia resonance system, a control system is designed such that a transfer function representing input-to-output torque is shaped in the frequency domain. Experimental results obtained using a prototype of the compound structure motor that incorporates an EMC demonstrate the effectiveness of the proposed concept.

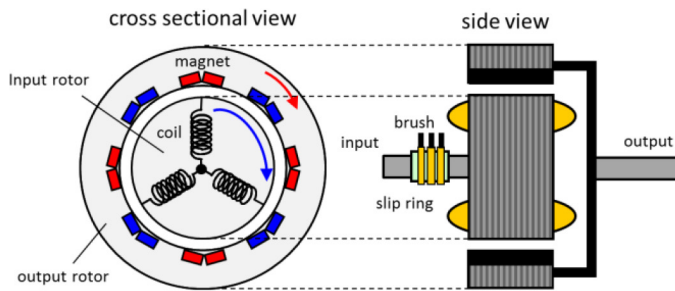


Figure 1. Structure of the electromagnetic coupling (EMC).

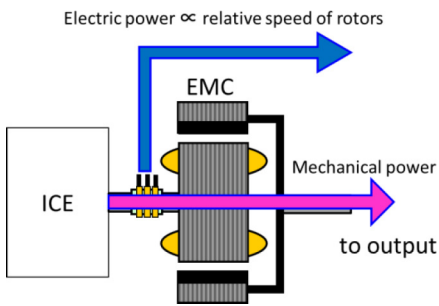


Figure 2. Basic function of the EMC.

ELECTROMAGNETIC COUPLING

Basic Function

As shown in Figure 1, the EMC is composed of a set of two rotors that are capable of rotating independently. One of the rotors has a structure in which permanent magnets are embedded, and the other has a winding coil structure. The rotors are referred to, respectively, as the magnet rotor and the winding rotor. A slip ring system attached to the winding rotor enables control of the rotating magnetic field of the winding rotor, making it possible to control the torque between the rotors. Therefore, the EMC is able to transmit torque from an input rotor to an output rotor with a contactless structure, also enabling control of the input speed. While transmitting torque, the EMC generates electric power or is driven by electric power. In Figure 2, the power flow of the EMC, in which the mechanical input power is transferred to the output shaft by splitting the input power into mechanical power and electric power, is shown. Therefore, by attaching another traction motor at any point on the output driveline of the EMC system, the electric power generated by the EMC can be used to amplify the input torque.

In this way, the EMC, in conjunction with another traction motor placed at arbitrary point on the output driveline of the EMC, can be used as a continuously variable transmission in various drivetrain systems for hybrid electric vehicles.

Principle of Vibration Interception

In addition, the EMC has a characteristic whereby the transmitted torque can be made arbitrarily smooth, even if the input torque includes fluctuation, as in the case of ICE torque. This is due to the contactless transmission structure. Hence, the EMC is expected to be used as a torsional damper in addition to the power splitting function in the drivetrain system. In order to specify the original characteristics of the EMC, a powertrain system attached to a traction

motor and a powertrain system attached to an EMC are shown in Figure 3. In the powertrain system with the EMC, the output driveline is mechanically disconnected from the ICE, whereas in the powertrain with a traction motor, the output driveline is mechanically connected to the ICE.

As a consequence of the difference between these powertrain systems, the vibration suppression behavior using electric machines is different. Figure 4 shows the principal vibration suppression behavior of both powertrain systems, which is obtained by simulations conducted under the condition of fluctuating input torque for the ICE.

In each system, a smooth torque is transmitted to the output driveline, although the input torque includes fluctuation. However, the torque behavior of each electric machine is different. The powertrain system with EMC generates smooth torque, which is required for the output, whereas the system with a traction motor needs to generate a fluctuating counter torque that cancels out the fluctuating input torque. Generating the counter torque requires a precise prediction of the fluctuating torque, which will be transmitted to the input shaft of the traction motor.

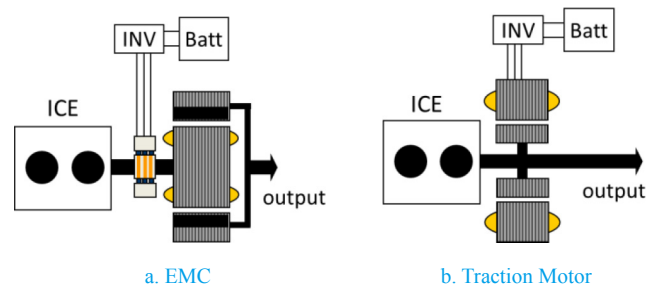


Figure 3. Comparison of the powertrain architectures with (a) an EMC and (b) a traction motor.

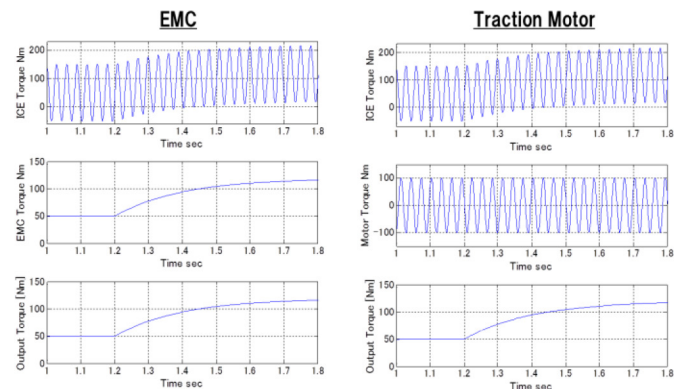


Figure 4. Comparison of the vibration suppression behavior of (a) an EMC and (b) a traction motor.

SYSTEM MODELING FOR CONTROL

Control Purposes

In order to use the EMC system as a continuously variable transmission in conjunction with vibration suppression, a control system design of an EMC applied to a powertrain system is considered. The purposes of controlling the EMC are

1. controlling the speed of the input rotor such that ICE can operate on the optimal thermal efficiency line, and
2. transmitting smooth torque to the output shaft, while intercepting the fluctuating torque generated by the ICE to be transmitted to the output shaft.

The speed of the input rotor can be controlled using feedback control of the engine speed and feedforward control of the ICE torque. Since the frequency band for the fluctuating torque of the ICE can be estimated by the proposed ICE operation, control design for intercepting the fluctuating torque can be performed by shaping a transfer function representing the ICE torque to the EMC torque. In order to achieve these goals, control design is performed based on a mathematical model.

A system architecture using the EMC described in Figure 5 is considered in the present paper. This architecture may be applicable as a powertrain for hybrid electric vehicles. In this architecture, a stator is attached outside the EMC, enabling to add motor torque to the outer rotor of the EMC. This compound structure electric machine is referred to as the electromagnetic torque converter eMAT, the characteristics of which will also be presented at SAE 2016 [8].

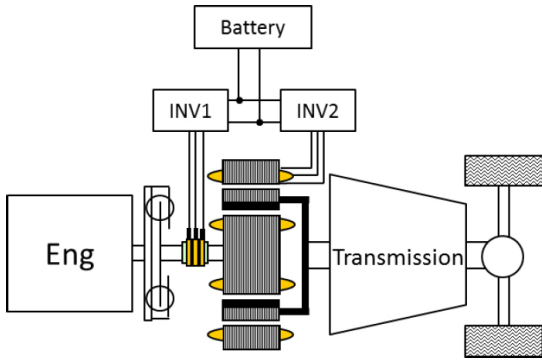


Figure 5. Hybrid system architecture using an EMC.

Mathematical Model

In order to consider vibration interception control for the powertrain system shown in Figure 5, a mathematical model representing the dynamical behavior of the input shaft of the EMC is introduced. In the powertrain system shown in Figure 5, the input shaft, which is composed of a crank shaft, a flywheel, a damper, a slip ring, and a winding rotor, can be represented by the two-inertia resonance model shown in Figure 6.

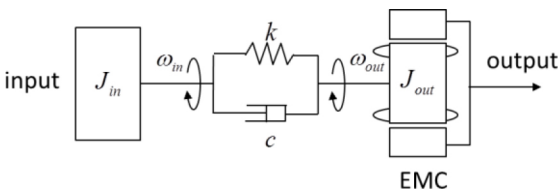


Figure 6. Two-inertia resonance model representing the input shaft behavior of the powertrain system using an EMC.

For this model, the system equations can be written as

$$J_{in} \dot{\omega}_{in}(t) = T_{in}(t) - T_{tor}(t) - T_{fin} \quad (1)$$

$$J_{out} \dot{\omega}_{out}(t) = T_{tor}(t) - T_{EMC}(t) - T_{fout} \quad (2)$$

$$T_{tor}(t) = k(\theta_{in}(t) - \theta_{out}(t)) + c(\omega_{in}(t) - \omega_{out}(t)), \quad (3)$$

where t represents the time variable, and other variables and physical parameters are defined in Table 1. For ease of analysis, the friction torques T_{fin} and T_{fout} are set to be zero by including them in a viscous friction term in T_{tor} . By applying a Laplace transform to equations (1) to (3) and setting the initial values of the variables to zero, we obtain the following equation:

$$\begin{pmatrix} \omega_{in}(s) \\ \omega_{out}(s) \end{pmatrix} = \begin{pmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{pmatrix} \begin{pmatrix} T_{in}(s) \\ -T_{EMC}(s) \end{pmatrix}, \quad (4)$$

where s is the Laplace transform variable and can take values of the complex number. The transfer functions appearing in the above equation are represented as

$$P_{11}(s) = \frac{J_{out}s^2 + cs + k}{poly(s)} \quad (5)$$

$$P_{12}(s) = \frac{cs + k}{poly(s)} \quad (6)$$

$$P_{21}(s) = \frac{cs + k}{poly(s)} \quad (7)$$

$$P_{22}(s) = \frac{J_{in}s^2 + cs + k}{poly(s)} \quad (8)$$

where the characteristic polynomial is defined as follows:

$$poly(s) = s\{J_{in}J_{out}s^2 + (J_{in} + J_{out})cs + (J_{in} + J_{out})k\}. \quad (9)$$

The block diagram representing the input-to-output relationship of equation (4) is shown in Figure 7.