Experimental Verification of Sensing Capability of an Electromagnetic Induction System for an MR Fluid Damper-based Control System

H J Jung1, D D Jang1, S W Cho2 and J H Koo3
1Dept. of Civil & Environmental Engineering, KAIST, 305-701, Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea
2Samsung SDS Co., Ltd., Yeoksam-dong, Gangnam-gu, Seoul 135-918, Korea
3Dept. of Mechanical & Manufacturing Engineering, Miami Univ., Oxford, Ohio 45056, USA
E-mail: hjung@kaist.ac.kr

Abstract. This paper investigates the sensing capability of an Electromagnetic Induction (EMI) system that is incorporated in a vibration control system based on MR fluid dampers. The EMI system, consisting of permanent magnets and coils, converts reciprocal motions (kinetic energy) of MR damper into electrical energy (electromotive force or emf). According to the Faraday’s law of electromagnetic induction, the emf signal, produced from the EMI, is proportional to the velocity of the motion. Thus, the induced voltage (emf) signal can be used to provide the necessary measurement information (i.e., relative velocity across the damper). In other words, the EMI can act as a sensor in the MR damper system. In order to evaluate the proposed concept of the EMI sensor, an EMI system was constructed and integrated into an MR damper system. The emf signal is experimentally compared with the velocity signal by conducting a series of shaking table tests. The results show that the induced emf voltage signal well agreed with the relative velocity.

1. Introduction

The magnetorheological (MR) fluid dampers have received considerable attention for vibration mitigation of structures in the field of civil engineering because of their attractive features such as mechanical simplicity, high dynamic force range, and low operating power [1]. The semi-active control system based on MR fluid dampers should include a feedback control system including an external power supply, a controller, and sensors, which may cause maintenance and cost problems, particularly for large-scale civil engineering structures, such as high-rise buildings and cable-stayed bridges. In an effort to solve the abovementioned problems, the smart passive system, which consists of an MR fluid damper and an electro-magnetic induction (EMI) system, has been recently developed by the authors [2]. The EMI system consisting of permanent magnets and a coil is capable of generating power by converting mechanical energy (i.e., reciprocal motions of an MR fluid damper) into electrical energy (i.e., electromotive force or induced voltage) based on the Faraday’s law of induction [3]. As such, the EMI was studied as an alternative power source for MR dampers to

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eliminate an external power supply. In a recent study, the authors demonstrated the powering ability of the EMI system by operating an MR damper device using the harvested energy [4].

In addition to the energy harvesting capability, the EMI system can provide a sensing capability. This is because the induced voltage (emf) from the EMI system is linearly proportional to the relative velocity across the MR fluid damper according to the Faraday’s law. This principle, in fact, has been used in commercial, inductive velocity transducers. The EMI’s sensing capability can be useful in the MR fluid damper-based control systems because some control algorithms require the measurement information on the response related to the relative velocity of the damper. As such, this study examines the sensing capability of the EMI system experimentally using a prototype EMI system.

2. Electromagnetic Induction System

Figure 1 shows the schematic of the EMI system augmented in an MR damper and the prototype of the large-scale EMI system installed in a shaking table.

![Schematic of EMI system](image)

**Figure 1.** The Electromagnetic Induction System

The electromotive force (or the induced voltage) produced by the EMI system can be expressed as

$$\varepsilon = -N \frac{d\Phi}{dt} = -N \frac{d(\Phi A)}{dt} = -NB \frac{dA}{dt} = -NBw \frac{dx}{dt}$$  \(\text{(1)}\)

where \(\varepsilon\) is the induced electromotive force (emf) in volts; \(N\) is the number of turns of coil; \(\Phi\) is the magnetic flux in webers; \(B\) is the magnetic field; \(A\) is the area of cross section; \(w\) is the coil width; and \(x\) is the relative displacement of the permanent magnet. Negative sign in equation (1) is the direction of the induced current.

As shown in equation (1), the induced emf (\(\varepsilon\)) in a closed loop is equal to the negative value of the time rate of change of magnetic flux through the loop, and it is also proportional to the relative velocity across the MR fluid damper. According to the Faraday’s law, therefore, the EMI system can be considered as a velocity sensor for the MR fluid damper. It might be used in the MR fluid damper-based semi-active control systems that require the relative velocity information to implement them. Figure 2 shows the block diagram of the semi-active control system using the EMI device as a velocity sensor as well as a power supply.

![Block diagram of MR fluid damper-based semi-active system using EMI system](image)
3. Experimental Validation

In order to validate the EMI system’s sensing capability, a series of shaking table test are carried out under various loading conditions. Figure 3 compares the relative velocity of the MR damper along with the induced voltage signal generated from the EMI under several harmonic input excitations. In this experiment, the relative velocity of the damper is calculated by differentiating the measured displacement from the shaking table. As seen from Figure 3, the time history responses of the relative velocity of the MR fluid damper match well with those of the induced voltage from the EMI system.

![Figure 3. Time history responses of the induced voltage from the EMI system and the relative velocity of the MR fluid damper with various harmonic input frequencies](image)

To further characterize the relationship between the relative velocity across the MR fluid damper and the induced voltage from the EMI system, their peak amplitude values are compared. As shown in Figure 4, the trend line of the data points is linear, indicating that the induced voltage signal is linearly proportional to the velocity signal. This result suggests that the EMI system may be used as a velocity sensor.

![Figure 4. Relationship between the peak relative velocity and the peak induced voltage](image)

In addition to the harmonic inputs, scaled historical earthquake excitations (El Centro and Kobe earthquakes) are used to further validate the EMI’s sensing capability. Before presenting the results, it is noteworthy that some semi-active control algorithms currently being used in the MR damper-based control systems, such as the maximum energy dissipation algorithm, often require just a direction of the relative velocity across the damper (i.e., its sign change), not exact velocity amplitudes. In other
words, it is sufficient to implement such control algorithms if the sign (or phase) of the induced voltage from the EMI system coincides with that of the relative velocity across the damper. Thus, the degree of agreement between signs of the induced voltage and the relative velocity, under the two scaled earthquake records, are compared in Table 1.

Table 1. Degree of agreement between signs of the voltage and the velocity (%)

| Earthquake | $|v| > 5\text{ mm/s}$ | $|v| > 10\text{ mm/s}$ | $|v| > 30\text{ mm/s}$ |
|------------|----------------------|----------------------|----------------------|
| El Centro  | 98.55                | 100                  | 100                  |
| Kobe       | 95.77                | 95.52                | 100                  |

As shown in Table 1, the degree of the sign agreement is slightly velocity dependent, yet the signs of the induced voltage and the relative velocity match well, over 95 % at lower velocities. Moreover, the signs completely match when the velocity is relatively large (i.e., 30 mm/s). The results indicate that the EMI system can be used as a “relative velocity” sensor for the MR damper-based semi-active control system, employing phase based control algorithms (for example, the maximum energy dissipation algorithm).

4. Conclusions
The sensing capability of the EMI system, incorporated in the MR fluid damper-based semi-active control system, is experimentally investigated. After constructing a prototype EMI system, it is augmented to an MR damper system installed in a shaking table. A series of shaking table experiments were conducted to compare the induced emf (or voltage signal) from the EMI and the velocity signal under various harmonic and scaled historic earthquake loading conditions. The experimental results validated that the linear relationship between the induced emf and the velocity signal, as expected based on the Faraday’s law of induction. Thus, the results indicate that the EMI system may be considered as a velocity sensor, albeit more thorough investigation should be required to use it as a velocity sensor. The results further show that the EMI system can be used as a “velocity-sign” sensor because the sign change of the emf signal agrees well with that of the velocity signal. This characteristic of the emf signal might be particularly useful for control algorithms that only require sign change of the velocity signals.

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