A new energy-harvesting device system for wireless sensors, adaptable to on-site monitoring of MR damper motion
Technical Note

A new energy-harvesting device system for wireless sensors, adaptable to on-site monitoring of MR damper motion

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Abstract

Under extreme service conditions in vehicle suspension systems, some defects exist in the hardening, bodying, and poor temperature stability of magnetorheological (MR) fluid. These defects can cause weak and even invalid performance in the MR fluid damper (MR damper for short). To ensure the effective validity of the practical applicability of the MR damper, one must implement an online state-monitoring sensor to monitor several performance factors, such as acceleration. In this empirical work, we propose a new energy-harvesting device system for the wireless sensor system of an MR damper. The monitoring sensor system consists of several components, such as an energy-harvesting device, energy-management circuit, and wireless sensor node. The electrical energy harvested from the kinetic energy of the MR fluid that flows within the MR damper can be automatically charged and discharged with the help of an energy-management circuit for the wireless sensor node. After verifying good performance from each component, an experimental apparatus is built to evaluate the feasibility of the proposed self-powered wireless sensor system. The measured results of pressure, temperature, and acceleration data within the MR damper clearly demonstrate the practical applicability of monitoring the operating work states of the MR damper when it is subjected to sinusoidal excitation.

Keywords: magnetorheological (MR) fluid, energy harvesting device, wireless sensor node, energy management circuit

(Some figures may appear in colour only in the online journal)

1. Introduction

Magnetorheological (MR) fluid is a type of field-controllable fluid whose rheological properties can be changed under an external magnetic field. MR fluids are widely and successfully used in MR dampers, which can provide controllable damping forces in semiactive control devices [1]. Recently, MR dampers have received considerable attention for their attractive features, including mechanical simplicity, continuously controllable force, rapid response, low power consumption, and environmental robustness [2–4]. However, under extreme service conditions, some defects may exist in the hardening, bodying, and poor temperature stability in MR fluids. These defects can cause weak and even invalid performance in MR dampers [5, 6]. Thus, an online monitoring sensor system is needed to detect malfunction in MR dampers during dynamic motion. The sensor system, like many other structural-health-monitoring systems, can predict damage in the MR damper, serving as an early warning system to prevent unexpected accidents. In addition, the inner-state
parameters obtained from the sensor system can be used to evaluate performance variation in MR dampers.

Real-time monitoring of inner states in MR damper operation is a challenging and meaningful research field. In MR dampers, confined and limited space, as well as a hydraulic and dynamically driven environment, can cause unexpected problems and malfunctions. However, in recent years, technological advancements associated with advances in sensors, low-power integrated circuits, and wireless communications are increasingly facilitating real-time monitoring of various dynamic systems such as flexible structures and damper systems. Since an MR damper is a type of energy-dissipating device, the dissipated energy can be partially harvested and converted into useful electrical energy with an energy-harvesting device. Recently, some researchers have proposed innovative solutions on damper-based vibration energy harvesting, notably in smart fluid-damper-based mechanisms. A rack-and-pinion mechanism attached to the hydraulic cylinder of an electrorheological (ER) shock absorber was designed to produce electrical energy for the control system of the ER shock absorber [7, 8]. We also studied the possibility of using a rack-and-pinion mechanism, associated with a linear-permanent DC generator, to drive the MR damper, using the control circuit and power supply to sense structure vibration [9]. An electromagnetic induction system attached to one side of the MR damper was also used to produce electrical energy to operate the damper [10, 11]. In addition, a self-powered MR damper (operated using the energy harvested from both its operating environment and the energy-harvesting device, which consists of a stator, a permanent magnet, and a spring [12]) was proposed and studied. An electromagnetic induction device consisting of permanent magnets and a coil has been used to produce electric energy for MR fluid dampers [13]. A permanent magnet generator, attached to the MR damper and consisting of a stator, a permanent magnet, and a spring, was designed to supply power to the MR damper by operating as an garnering, dynamic vibration absorber [14]. The possibility that an electromagnetic structure of stator and mover can act as a power generator for a self-powered, self-sensing MR damper has also been studied [15].

Unlike the aforementioned energy-harvesting devices used in vibration control systems in smart, fluid-based dampers, we designed a novel, energy-harvesting device attached to the piston head of an MR damper to partially convert the kinetic energy of MR fluid flow within the MR damper into electrical energy for the wireless sensor node. This is the main difference of the proposed wireless sensing system from the previous energy-harvesting systems for smart, fluid-based dampers. Compared with the aforementioned devices, the proposed energy-harvesting device is relatively small and works within the MR damper. This method allows the integrated system of the monitoring sensor node to be easily designed. The energy-harvesting system proposed in this work consists of an energy-harvesting device, an energy-management circuit, and a wireless sensor node. The energy-harvesting device can reduce the cost of the wireless sensor node by minimizing the need for costly wiring and replacement batteries. The energy-management circuit makes full use of the electrical energy harvested to efficiently power the wireless sensor node, which monitors the on-suit inner states of the MR dampers. To demonstrate the effectiveness and practical feasibility of the proposed energy-harvesting system, we built an experimental apparatus that associates with manufactured components such as the energy power-management circuit. The temperature, pressure, and accelerometer of the MR damper are measured under sinusoidal excitations, which are the same operating conditions as those seen in a vehicle damper.

2. Energy-harvesting system for the wireless sensor

Figure 1 shows the proposed energy-harvesting system in which we see the printed circuit breadboard (PCB), electromagnetic energy converter, and sensor node. The energy-harvesting device can partially convert the kinetic energy of the fluid flow within the MR damper into electrical energy. The energy-management circuit makes full use of the harvested electrical energy to efficiently power the wireless sensor node, which monitors on-suit inner states of the MR damper. The sensor data within the MR fluid damper can be efficiently transmitted and displayed on a computer’s liquid crystal display (LCD). We note that the behavior of the MR damper is not significantly affected by the impeller. In fact, we completed comparative experiments between the custom MR damper and the MR damper with the impeller for this
paper. We identified that the damping force of the MR damper with an impeller is relatively bigger than the damping force of the custom MR damper. This is because the viscous damping force is increased due to the longer channel increments in the MR damper with the impeller. However, the energy-harvesting structure proposed in this paper has not been affected by this change in damping force.

2.1. Harvesting device

The energy-harvesting device is mainly comprised of an electromagnetic energy converter, an impeller, and a sealing unit, as shown in figure 1. When applied load is acted on by the MR damper, MR fluid will be forced through the damping channel and the impinging blades of the impeller, which can change the velocity direction of the movement of the MR fluid. The impeller produces torque and rotates with the changing momentum of the MR fluid flow. The electromagnetic energy converter and impeller are coaxially connected and incorporated into the energy-harvesting device. Thus, corresponding electrical energy can be generated by the electromagnetic energy converter, which runs with the impeller. The relationship between the average power of the kinetic energy of fluid flow $P_{\text{flow}}$ and the average electrical power $P_t$ generated is given by

$$P_t = \eta P_{\text{flow}}$$

(1)

where $\eta$ is the total conversion efficiency of the energy-harvesting device. Figure 2 shows a photograph of several components of the energy-harvesting device. The electromagnetic energy converter is enclosed within the sealing unit and axially connected to the impeller. The energy-harvesting device is used as the power for the real-time monitoring sensor system of the MR damper.

2.2. Energy-management circuit and wireless sensor node

Because of low output voltage, the harvested electrical energy cannot directly be used to power the wireless sensor node; hence, it needs to be adjusted by an energy-management circuit. As we see in figure 3(a), the energy-management circuit consists of several elements: a simple AC/DC rectification circuit assembled diodes SS14 with voltage drop 0.3 V, an ultra-capacitor $C_p$ (0.0474 F, 5.5 V), chip MAX6433 (made by MAXIM company), MOSFET, a voltage-regulator chip S1206B30, and resistances. MAX6433 is an energy-monitoring chip with adjustable threshold voltages, which permit the user to determine the low- and high-voltage thresholds by selecting different resistances $R_1$, $R_2$, and $R_3$. According to the dimensions of the sealing device, the circuit is built on a limited, round breadboard with 16 mm radii, as shown in figure 3(b). The circuit used in this work can be significantly improved in terms of energy consumption and work stability. The operating principle of this circuit is as follows: The voltage signal from the energy-harvesting device is rectified as full wave and accumulated in the ultracapacitor $C_p$. When the ultracapacitor $C_p$ voltage rises above the specified high-voltage threshold (4.32 V), the MOSFET triggers the acting analog switch, and the circuit is open. Similarly, when the ultracapacitor $C_p$ voltage drops below the specified low-voltage threshold (3.12 V), the MOSFET breaks and the circuit is open. In addition, during the discharge process, the output voltage signal remains constant with the help of S1206B30. The energy-management circuit can achieve a continuous charge-discharge cycle and allows the harvested energy to effectively power the wireless sensor node.

In this work, the wireless sensor node is composed of sensors, EEPROM, and a data processing and communication unit, as shown in figure 4(a). The data processing and communication unit selects a single chip system nRF9E5 (made by the Norwegian Nordic Corporation) which is a fully integrated RF transceiver of 8051. This is compatible with the microcontroller and a four-input, ten-bit, 80-kbps analog-to-digital (A/D) converter. The digital temperature sensor DS18B20, pressure sensor MPS27H1000, and acceleration sensor AD335 are chosen and used to monitor the on-suit inner temperature, pressure, and excitation acceleration of the MR damper, respectively. The sensor data is transmitted by the transmitter modules. Meanwhile, the sensor’s data is received by the receiver modules and transferred to the computer by the RS-232 interface. Figure 4(b) shows the PCB of the transmitter modules, built with receiver modules and 16 mm radii. The wireless sensor node can steadily transmit the sensor signals from the inner areas to the outer areas of the MR damper.

3. Results and discussions

3.1. Experimental setup

The MR damper used in this work has a monotube arrangement with pressurized air/nitrogen at the end of the pressure tube, which is separated from the MR fluid by a floating piston. The pressurized gas acts as an accumulator to compensate for volumetric changes caused by the moving piston rod, and the accumulator is pressurized with nitrogen to 180 kPa. The MR damper body is approximately 300 mm in
length and filled with MR fluid J01T, developed by the Chongqing Instrument Material Research Institute in China. The resistance of the excitation coil $R$ is 3 $\Omega$. The annular damping channel between the piston head and the hydraulic cylinder is 1.5 mm in height, 121 mm in average perimeter width, and 20 mm in effective length. We note here that the MR damper tested in this work is comparable to that found in a mid-sized passenger vehicle suspension.

The movement of the piston is controlled by an electromagnetic exciter (Model: MPA406-M232A) which is run by an electrodynamic controller in force or acceleration-feedback mode. The shaking table, shown in figure 5, has the following dynamic properties: 300 kg maximum test load, maximum acceleration of 981 m s$^{-2}$, maximum velocity of two m s$^{-1}$, maximum useful frequency of 3000 Hz, and a 51 mm stroke length. In this work, the MR damper is mounted to the shaking table and subjected to sinusoidal excitation mode with a 50 mm stroke.

3.2. Energy harvesting device

First, we evaluated the performance of the energy-harvesting device under different conditions. We used a three-phase, AC electromagnetic energy converter in this work. Thus, a tri-phase-bridge rectification circuit assembled by diodes IN4001 is used to convert the AC to DC; the microelectromagnetic energy converter is three-phase AC mode. The voltage of the resistive load $R'$ (11 $\Omega$) is collected by the in situ data-acquisition equipment (oscilloscope) with a one-millisecond data-collection interval time ($\Delta t$). The MR damper with the energy-harvesting device is mounted to the shaking table and subjected to sinusoidal input at excitation frequencies of 2 Hz, 2.5 Hz, 3 Hz, 3.5 Hz and 4 Hz. The input currents supplied to the MR damper are 0 A, 0.5 A and 1 A, respectively. Based on a load voltage $U$, the average electrical power harvested $P$ can be calculated by

$$P = \frac{\sum_{i=1}^{n} U_i^2 \Delta t}{(R'T)}$$

where $n = T/\Delta t$ and $T$ is the test cycle. The results at each different excitation frequency are summarized in table 1. Table 1 shows the subtle differences that measured energies with different input currents have on the MR fluid at the same frequency. We can see that the input currents to the MR damper have little effect on the electrical energy harvested, especially at lower frequencies. We note that the harvested electrical energy is enough to power the wireless sensor node, which is required for the practical operation of the MR damper.

3.3. Energy management circuit

To verify the feasibility of using the electrical energy-harvesting system for the wireless sensor node, we conducted...
another experiment. The electrical energy obtained for the wireless sensor system can automatically charge and discharge with the help of the power-management circuit. The MR damper with the energy-harvesting device is mounted to the shaking table in a sinusoidal motion and tested with an exciting frequency of 4 Hz and an amplitude of 20 mm. The energy-harvesting device continuously charges the ultracapacitor, even during the discharge course of the ultracapacitor. Figure 6 shows the continuous charge and discharge process of the ultracapacitor with a voltage signal, and we see that the electrical energy harvested can continuously meet the demand of the wireless sensor node. We note that the output voltage remains stable with the help of voltage-regulator chip S1206B30. The interval between two low voltages shown in figure 6 represents a data-transmission duty cycle.

Figure 4. Wireless sensor node (a) schematic diagram and (b) photograph of PCB.

Figure 5. Test facility of the energy-harvesting system associated with the MR damper.
Due to special service conditions and environment, the electromagnetic energy converter, energy-management circuit, and wireless sensor nodes are all integrated into a finite volume of 46 cm³ which is attached to the piston head of the MR damper. The sensors are arranged on the sides of the piston head to measure the inner state of the MR damper. The MR damper attached to the proposed energy-harvesting system is mounted on the shaking table and tested in a sinusoidal excitation with a 35 mm stroke and a 4 Hz frequency. During the excitation, input currents of 0 A, 0.5 A, 1.0 A, and 1.5 A are applied to the fluid domain of the MR damper. The sensor’s data are efficiently transmitted and displayed on the LCD of the computer. Figure 7 shows the experimental temperature/time history curves. The temperature data collected is relatively smooth and not interfered with by circumstance. The temperature increases at the same increments as the input currents to the MR damper, because the input current is one of the heat producers in the MR damper with the term $I^2Rt$. The temperature/time curve with input current 0.5 A intersects the temperature/time curve with input currents 1 A and 1.5 A. In addition, we observe that the initial temperature for input current 0.5 A is higher than that of input currents 1 A and 1.5 A. The temperature in figure 7 looks like it has linear increments, but that is not because the temperature curve of the MR damper is not linear. The monitoring sensor system can implement online state monitoring sensors to detect several performance factors within the MR damper, such as temperature. The operating temperature of the MR damper is not higher than 80 °C in this work. We see through experiments that the monitoring sensor system can work well at 53 °C. However, the energy-harvesting device system can endure temperatures much higher than 80 °C if we use an epoxy resin to seal it. The measured pressure/time history is shown in figure 8. We see that the peak pressure value within the MR damper presents its safe state. We also observe that the pressure increases as the input current applied to the MR damper increases. The input currents can strengthen the MR effect and make the inner pressure increase. In other words, as the input current increases, the damping force increases. The test is conducted with sinusoidal excitation conditions: a 35 mm stroke and a 4.0 Hz frequency. The measured time histories of accelerations are the same and unrelated to the different input currents applied to the MR damper, as shown in figure 9.

Based on the above experimental results, we know that the electrical energy harvested from the proposed system is sufficient to operate the wireless sensor node and is efficiently managed by the energy-management circuit. We note that 30 m is the maximum transmission distance of the system, as identified by the experiment. The MR damper is in motion during the course of data transmission. However, the transmission of the sensor signal is not affected by the movement of the MR damper. The MR damper tested in this work is comparable to that found in a mid-sized passenger vehicle.
suspension, and sinusoidal excitation is used. When the maximum velocity of sinusoidal excitation is over 0.471 m s\(^{-1}\), the energy harvested can meet the demands of the system. According to the experiments, the frequency range is 3–5.5 Hz under the sinusoidal amplitude excitation 0.015–0.025 m. In these conditions, the MR damper could work without affecting data transmission.

4. Conclusion

In this paper, we proposed a new type of energy-harvesting device system for the wireless sensing of inner-state conditions in the operation of MR dampers. The proposed system has been empirically realized to validate its practical feasibility in real environmental conditions. The proposed system integrated several components, such as an energy-harvesting device, an energy-management circuit, and a wireless sensor node. After verifying good performance for each component, we conducted an experiment monitoring the real-time inner state of the MR damper. We demonstrated that the energy-harvesting device could feasibly produce the electrical energy used by wireless sensor node with the help of an energy-harvesting device system with energy generation and application of an MRF damper-based smart passive control system employing an electromagnetic induction device. In addition, we showed that the effect of applied input currents on the MR damper does not significantly affect the electrical energy harvested. The temperature, pressure, and acceleration data tested under sinusoidal excitation and different currents applied to the MR damper indicate that the proposed system can efficiently monitor the inner-work states during MR damper motion. Lastly, we note that MR fluid only exhibits a viscous behavior like Newtonian fluid in the absence of a magnetic field. Thus, the proposed self-powered, real-time monitoring sensor system of the MR damper can be also applied to some hydraulic vehicle dampers without any significant modifications.

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