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Design and Experiment of an Electromagnetic Vibration Exciter for the Rapping of an Electrostatic Precipitator

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The miniaturization of an electrostatic precipitator has become a key element in successfully constructing an efficient electrostatic precipitator because of the limited space allowed for installation in a subway tunnel. Therefore, the miniaturization of the rapping system of the electrostatic precipitator has also become important. This research proposes a resonant-type electromagnetic vibration exciter as a vibrating rapper for an electrostatic precipitator. The compact vibrating rapper removes collected dust from the collecting plates without direct impact on those collecting plates. To characterize the dynamic performance of the electromagnetic vibration exciter, finite element analysis was performed using a commercial electromagnetic analysis program, MAXEWLL. Moreover, we analyzed the resonant frequency of an electrostatic precipitator, to which the electromagnetic vibration exciter was applied, by ANSYS. Also, to measure the acceleration generated by the electromagnetic vibration exciter, we manufactured a prototype of the ESP and electromagnetic vibration exciter and measured its acceleration at the resonant frequency.

Keywords : electromagnetic vibration exciter, vibrating rapper, electrostatic precipitator, dynamic performance analysis, vibration characteristics analysis, acceleration measurement, resonance

1. Introduction

Recently, with the subway becoming the key mode of public transportation, indoor air quality maintenance has become an important issue [1]. The air in the subway tunnel needs to be purified during the operation of subway trains because the air in the tunnel flows into the subway train. To reduce the amount of air pollutants in the subway tunnel, electrostatic precipitators (ESP) are widely used [2]. The ESP electrifies, collects and removes pollutants from the air in the tunnel. There are two types of ESP, wet and dry, depending on the cleaning methods of collecting plates [2, 3]. Wet ESP removes collected dust by continuously forming water layers on the surface of the collecting plates. On the other hand, dry ESP removes collected dust by an impact process [3, 4].

Figure 1 shows a schematic diagram of the installation space of an ESP system in a subway tunnel. The ESP system will be installed in the ventilation room for security reasons and because there is limited space in the subway tunnel. However, the installation space in the ventilation room is also limited. Thus, to improve the air quality in the tunnel using an air purifier, it is crucial to minimize the size of ESP system considering the difficulty of its installation due to limited space. Accordingly, a dry ESP is more suitable than a wet ESP because it has a simpler structure than the wet ESP and unlike the wet ESP, it does not breakdown in winter and does not require additional devices like a pump [3].

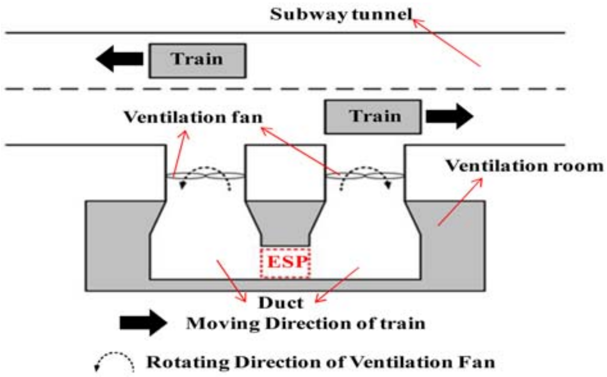

Fig. 1. (Color online) Schematic diagram of the installation space for an ESP system in a subway tunnel.

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Three rapping devices are available for the dry ESPs: motor-driven swing hammer, magnetic rapper and vibrator [4]. However, the motor-driven swing hammer and magnetic rapper are too large. Thus, these devices are difficult to install in the subway tunnel, and they may also damage the collecting plates by continuous impacts on the collecting plates. Also, a conventional vibrator cannot be used because it generates a very small acceleration. Also, to remove the collected dust such as fly ash or Particulate Matter-10 (PM-10) which means 10 micrometer of particle diameter, the acceleration of between 20 and 50 g is needed [4-6].

Therefore, in this research, we propose a resonant-type electromagnetic vibration exciter for the vibrating rapper of an ESP of compact size and that has the ability to remove the collected dust from the collecting plates without any direct impact on the collecting plates. In this paper, to characterize the dynamic performance of the electromagnetic vibration exciter, finite element analysis was performed using a commercial electromagnetic analysis program, MAXEWLL. Moreover, we analyzed the resonant frequency of the electrostatic precipitator, which the electromagnetic vibration exciter was applied to, by using ANSYS. Also, to measure the acceleration generated by the electromagnetic vibration exciter, we manufactured a prototype of the ESP and electromagnetic vibration exciter and measured its acceleration at the resonant frequency.

2. System Description of the Electromagnetic Vibration Exciter

Figure 2 shows a schematic diagram of the quadratic electromagnetic vibration exciter. It consists of an inner steel yoke with 4 rectangle-shape small permanent magnets, an outer steel yoke with 8 large permanent magnets, a coil, coil housing, case, stinger and plate spring. The inner and outer magnets create an enormous magnetic flux density in the air gap, which results in a strong magnetic force because the PMs are placed in a double layer. As such, the quadratic electromagnetic vibration generates a higher excitation force than a cylindrical electromagnetic vibration exciter. Also, the rectangle-shape PMs are easy to manufacture and magnetize [7, 8].

Figure 3 shows the operation principle of the electromagnetic vibration exciter. Two types of methods are available for the exciter operation: one is the moving coil

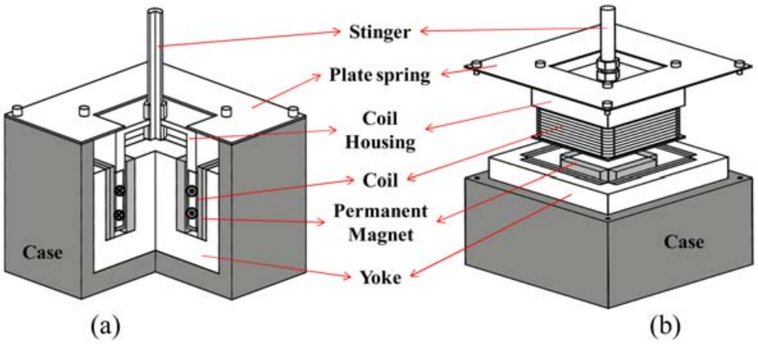


Fig. 2. (Color online) Schematic diagram of quadratic electromagnetic vibration exciter (a) assembled exciter (b) separated exciter.

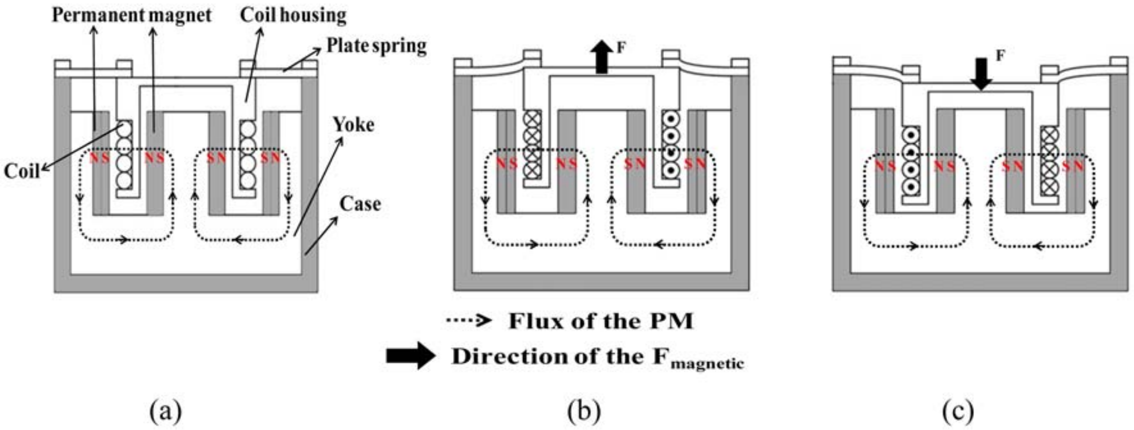


Fig. 3. (Color online) Operation principle of electromagnetic vibration exciter (a) at initial position (b) at upper position (c) at lower position.

method and other is the moving magnet method. In this research we use the moving coil method; the yoke and magnets are fixed while the coil moves. The vibration exciter is moved by the Lorentz force, this is created by the flux generated from the PMs and the sine wave current applied to the coil. The Lorentz force is expressed by Eq. (1).

$$F_{magnetic} = nB_g i l_{eff} \tag{1}$$

where n is the number of coil turns, B_g is the residual flux density of the PM in the air gap, i is the input current and l_{eff} is the effective length of coil in the air gap.

3. Dynamic Performance Analysis of the Electromagnetic Vibration Exciter

Figure 4(a) shows our 3D model of the electromagnetic vibration exciter. To verify the dynamic performance of the electromagnetic vibration exciter, finite element analysis (FEA) was performed using a commercial electromagnetic analysis program, MAXWELL. 3-D FEA, takes a tremendous amount of time, for this reason, Lee at al. suggested a 2D equivalent model to save simulation time [9]. Figure 4(b) shows the 2-D equivalent model which has a depth of 131 mm.

Table 1. Specification of the Neodymium PM.

Symbol	Parameter	Value
B_r	Residual induction	1.23 T
H_c	Coercivity	−890 kA/m
μ	Relative permeability	1.1

Table 2. Specification of the electromagnetic vibration exciter.

Symbol	Parameter	Value
m	Moving mass	1.6 kg
c	Damping coefficient	21.9 N·sec/m
k	Spring coefficient	750 kN/m
f_n	Natural frequency	108.96 Hz
i_0	Input current	4 A
turns	Number of coil turns	215 turns
f	Input frequency	80 Hz

A combined system of magnetic, electric and mechanical subsystem was used for the FEA. The nonlinear B-H characteristics of steel 1010 were applied to the yoke. The diameter of the coil was 1 mm and the coil housing was made of plastic. 12 rectangular-shape neodymium (Nd-Fe-B) permanent magnets were used. Table 1 shows the magnetic properties of the neodymium PM [9]. Table 2 shows the specification of electromagnetic vibration exciter. The spring coefficient was applied for the plate spring connecting the 26 collecting plates. That is, a total 27 springs were connected in parallel. Equation (2) is the motion equation of the mechanical subsystem. The mechanical subsystem including the moving mass and external force, and was governed by the second-order equation below.

$$m\ddot{x} + c\dot{x} + kx = F_{magnetic}(i) = nB_g l_{eff} i \tag{2}$$

The amplitude of the input current i_0 and the input frequency are given. The current flowing in the coil was expressed as a sine waveform, described by Eq. (3). The input frequency applied is 80 Hz because the resonance frequency of the ESP system is also 80 Hz, this figure was found from a vibration characteristics analysis. The magnetic force was also expressed as a sine waveform and oscillated the moving mass in the same pattern.

$$i = i_0 \sin(2\pi f t) \tag{3}$$

To solve the coupled system, transient FEA was performed with a time step of 0.2 milliseconds. Figure 5 shows the FEA results of the electromagnetic vibration exciter: displacement of moving mass, magnetic force, spring force and excitation force at the input current

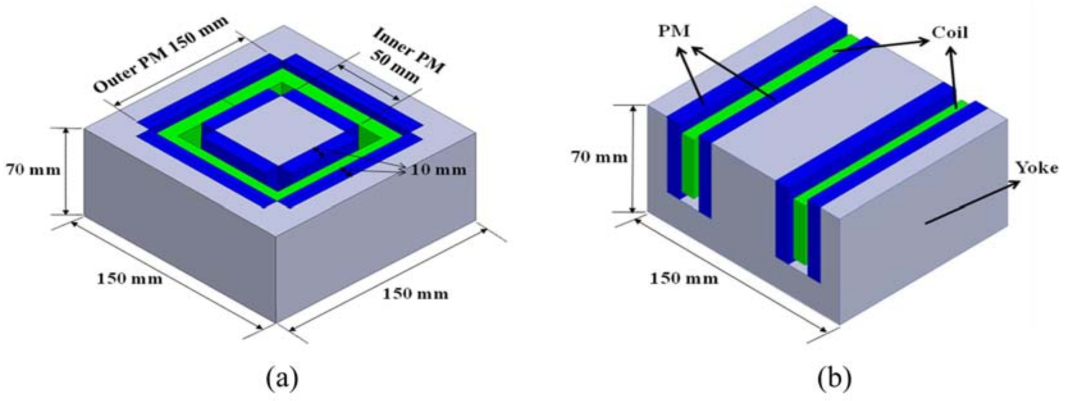
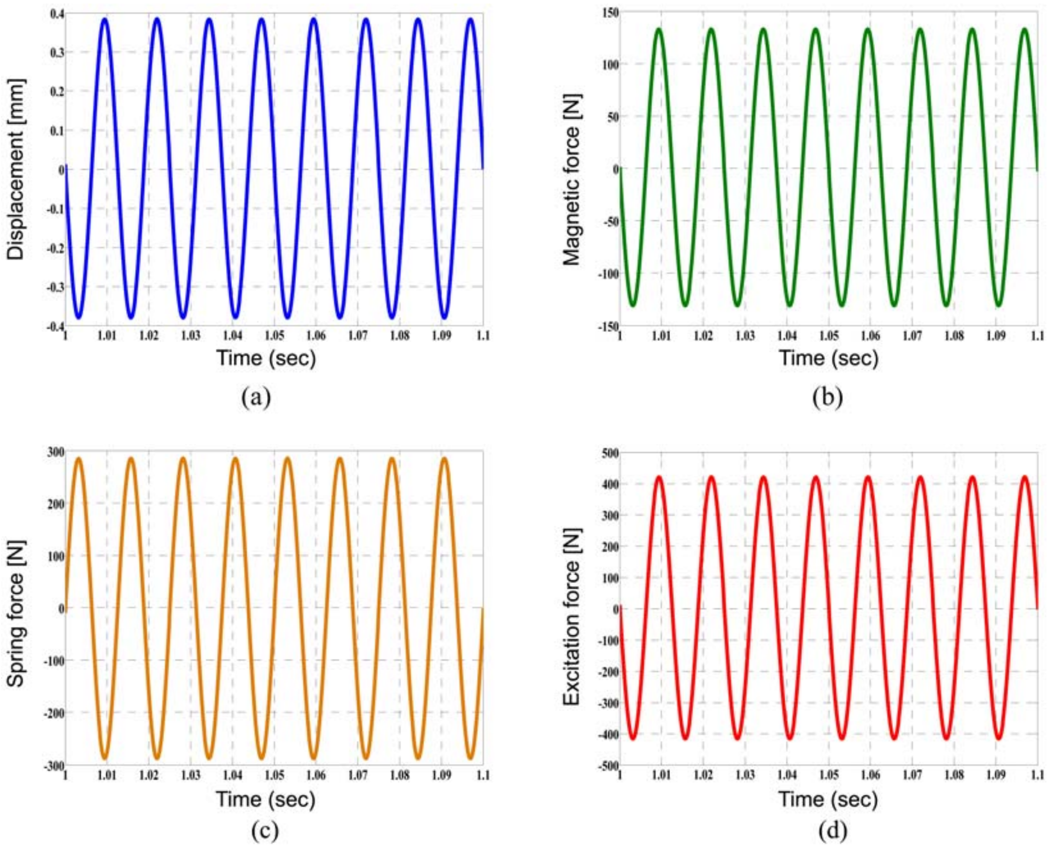


Fig. 4. (Color online) Simulation model of the electromagnetic vibration exciter (a) 3D model (b) 2D equivalent model.



(a) (b) (c) (d)

Fig. 5. (Color online) FEA results of the electromagnetic vibration exciter for (a) displacement (b) magnetic force (c) spring force (d) excitation force.

frequency of 80 Hz. The simulation has a steady-state response after 1 second. The transient response lasted for a short time, and the exciter was generally used in its steady-state. Therefore, the simulation results for 0.1 seconds after a steady-state was achieved are plotted. The displacement of the moving mass was about ± 0.4 mm, as shown in Figure 5(a). The magnetic force was about ± 130 N, as shown in Figure 5(b) and the spring force, which was determined by the displacement of the moving part, was about ± 290 N, as shown in Figure 5(c). As shown Figure 5(a) and 5(b), there was no phase difference between the displacement and the magnetic force because the natural frequency of the electromagnetic vibration exciter, which is 108.96 Hz, is higher than the input frequency of 80 Hz. Figure 5(d) shows the excitation force of the electromagnetic vibration exciter. The excitation force was approximately 420 N.

4. Vibration Characteristic Analysis of the ESP System

In order to analyze the resonant frequency of an ESP using the electromagnetic vibration exciter under steady-state excitation, harmonic analysis was performed using ANSYS. Figure 6 shows the simulation model of the ESP system. The ESP consists of 26 top and bottom fixed collecting plates. The electromagnetic vibration exciter is located at the center of the ESP and linked with the collecting plates. The simulation model applies a fixed boundary condition at the bottom of the floor. Harmonic analysis was performed from 1 Hz to 100 Hz at 1 Hz intervals. Figure 7 shows the result of the harmonic analysis for the ESP system. The resonant frequency is 80 Hz. Figure 8 shows the mode shape of the ESP system at resonant frequency.

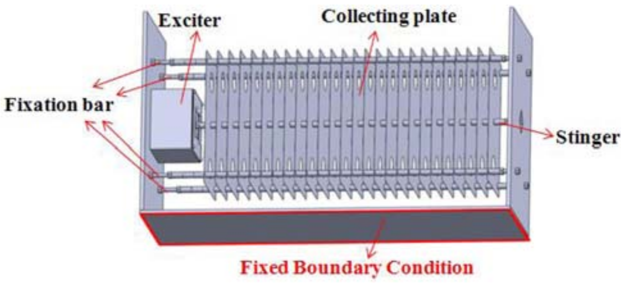


Fig. 6. (Color online) Simulation model of the ESP system.

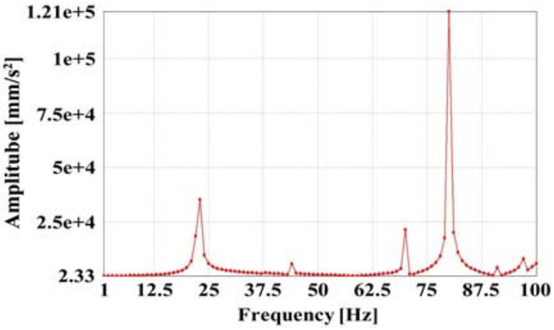


Fig. 7. (Color online) Result of harmonic analysis.

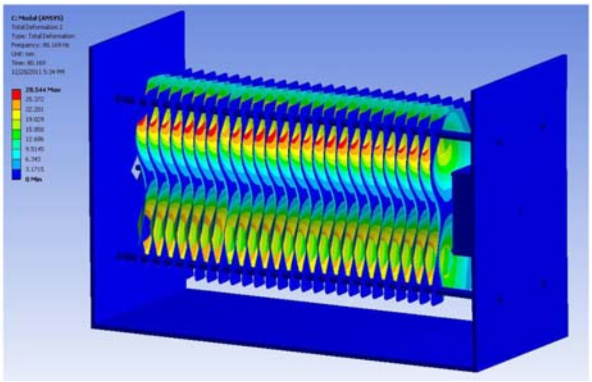


Fig. 8. (Color online) Mode shape of the ESP system at resonant frequency.

5. Experiments

To analyze the acceleration, we manufactured a prototype of the electromagnetic vibration exciter, as shown in Figure 9. It consists of a moving part which has a stinger, plate spring, coil and coil housing as shown in Figure 9(a) and a stationary part which has a yoke, PM and case as shown in Figure 9(b). Figure 10 shows the prototype of ESP with the electromagnetic vibration exciter. The ESP consists of 26 top and bottom fixed collecting plates which are made of 0.5 mm thick stainless steel. The vibration exciter removes collected dust from the center of the ESP. Figure 11 shows the experiment apparatuses. Experiment apparatuses consist of an AC power source for inputting current and frequency to the coil, a measuring instrument which can sample 10,000 pieces of data a second for measurement of the acceleration, a computer for monitoring data as shown in Figure 11(a) and an acceleration sensor for measuring acceleration in Figure 11(b). Figure 12 shows the experiment procedure. Once current and frequency were applied to the coil by the AC power source, the exciter vibrated. At that time, the acceleration was generated by the exciter and was measured by the acceleration sensor. Acceleration data was collected by the measuring instrument. The computer monitored overall acceleration data [10, 11].

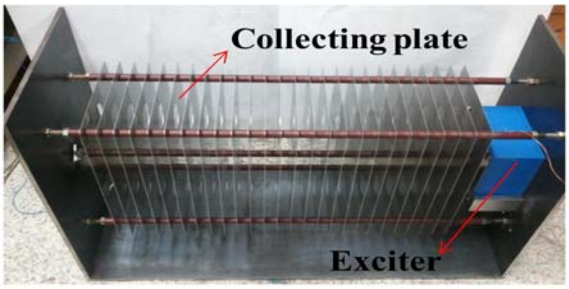
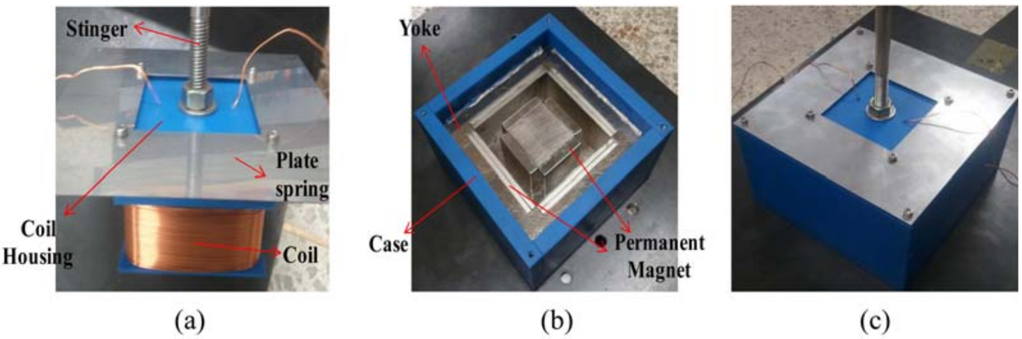


Fig. 10. (Color online) Prototype of the ESP system.

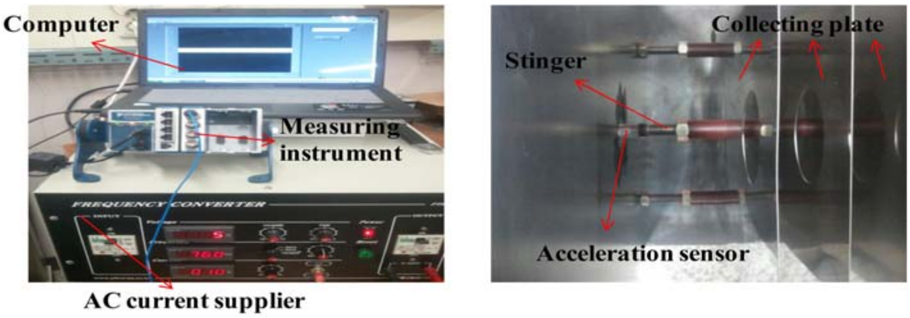
The acceleration was measured experimentally as the input frequency increased from 65 Hz to 85 Hz at 1 Hz intervals and the input current was increased from 1 A to 4 A. Figure 13 shows the attached position of the acceleration sensor at the collecting plate. Note, to remove collected dust, such as PM-10 or fly ash, an acceleration of between 20 and 50 g is needed.

Figure 14 shows the results of the acceleration measurement at the center of the ESP. The maximum acceleration was 450 m/s^2 when 4 A of current was applied. However, there was about 10% error between the resonant



(a) (b) (c)

Fig. 9. (Color online) Prototype of the electromagnetic vibration exciter (a) moving part (b) stationary part (c) assembled moving and stationary part.



(a) (b)

Fig. 11. (Color online) Experiment apparatuses (a) experimental setup (b) acceleration sensor setup.

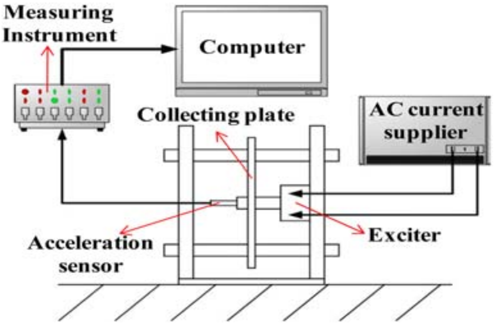


Fig. 12. (Color online) Experiment procedure.

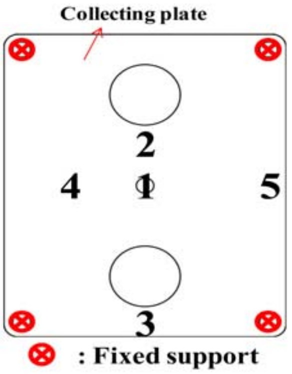


Fig. 13. (Color online) Attached position of the acceleration sensor on the collecting plate.

frequency of the harmonic analysis and the resonant frequency of the experiment because of errors associated with the prototype's manufacturing. The difference in the resonant frequency as input current increased from 1 A to 4 A was due to the current setting error. The maximum measurable acceleration of the acceleration sensor is 50 g. In addition, the measured acceleration results from the acceleration sensor in positions 2 to 5 was out of the maximum measurement range of the acceleration sensor at the input current of 1 A. Accordingly, we can say sufficient acceleration for rapping was generated. Therefore, if the proposed electromagnetic vibration exciter is

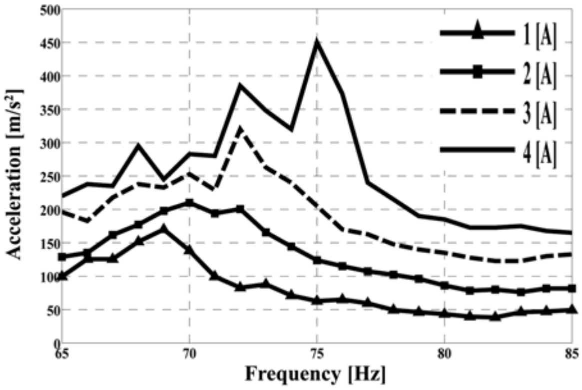


Fig. 14. Results of acceleration measurement at the center of the ESP.

applied as a vibrating rapper to the ESP, it will generate the required acceleration for rapping and can be used in limited space in subway tunnels.

6. Conclusions

This research proposes a resonant-type electromagnetic vibration exciter for the vibrating rapper of ESPs, the purpose of this device is to remove collected dust from the collecting plates of the ESP. The proposed device is sufficiently compact and does not directly impact the the collecting plates. In this paper, to characterize the dynamic performance of the electromagnetic vibration exciter, finite element analysis was performed. The displacement of the moving mass is about ± 0.4 mm. The magnetic force is about ± 130 N and the spring force is about ± 290 N. The excitation force is approximately 420 N. In addition, we analyzed the resonant frequency of the ESP, which the electromagnetic vibration exciter is applied to. The resonant frequency of the ESP system is 80 Hz. Also, to analyze the acceleration, we manufactured a prototype and measured the acceleration of the prototype at the resonant frequency. To remove the collected dust, such as

PM-10 or fly ash, an acceleration of between 20 and 50 g is needed. The proposed electromagnetic vibration exciter generated sufficient acceleration to remove the collected dust at any position of the collecting plates.

Therefore, if the proposed resonant-type electromagnetic vibration exciter is applied as a vibrating rapper of an ESP, it can be used in the limited space of a subway tunnel due to its compact size compared to a motor-driven swing hammer or magnetic rapper. Moreover, it can overcome disadvantages of a conventional vibrator by using resonance.

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