Seismic and Vibration Isolation of an Emergency Diesel Generator by Using a Spring-Viscous Damper System

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ABSTRACT

The effectiveness of a coil spring-viscous damper system for a vibration and seismic isolation of an Emergency Diesel Generator (EDG) was evaluated through a measurement of its operational vibration and seismic responses. The vibration measurement for an identical EDG set with different base systems - one with an anchor bolt system and the other with a coil spring-viscous damper system - was conducted during an operation to investigate the performance of a vibration isolation. The measurement showed that the vibration on the steel frame which supports the EDG set is significantly amplified but the vibration amplitude on the floor slab is negligible because much of the vibration on the steel frame is thoroughly isolated by the spring-damper system. A shaking table test for an EDG model was conducted for an evaluation of the seismic isolation performance of a coil spring-viscous damper system. An artificial time-history corresponding to the scenario earthquake for a Korean nuclear site was used as an input motion, and three peak acceleration levels were applied. The effectiveness of the coil spring-viscous damper system was evaluated by the ratio of the maximum acceleration responses measured at the model to the table acceleration. The vibration measurement during an operation of the EDG demonstrated that the spring-viscous damper system could reduce its mechanical vibration by more than 80 percent. Also, the EDG model tests showed that the spring-viscous damper system could reduce the seismic force transmitted to the EDG by up to 70 percent.

INTRODUCTION

Base isolation is a well-known and considerably mature technology to protect structures from strong earthquakes. A number of base isolation systems have been developed all over the world since 1970s. Some of them, for example rubber bearings and friction systems, have been adopted widely for buildings and civil structures such as bridges in several countries of a high seismicity, and their effectiveness has been demonstrated through surviving real strong earthquakes. The basic concept of a base isolation is to decouple a structure from the horizontal components of an earthquake ground motion by interposing a soft layer with a low horizontal stiffness between the structure and the foundation. This soft layer gives the structure a much lower fundamental frequency than its fundamental frequency for a fixed base and also much lower than the predominant frequencies of the ground motion. When a destructive earthquake occurs, since most of the deformation behavior is concentrated on the soft layer, the remainder of the structure will remain nearly elastic. Thus, a floor acceleration and interstory drift of the structure will be significantly reduced and also damage to the structural elements will be dramatically reduced. Also, the elastic behavior of the isolated structure will give a more reliable response than conventional structures.

In spite of the many potential advantages of a base isolation, however, the applications of a base isolation to nuclear facilities have been very limited because of a lack of sufficient data for the long-term operation of isolation devices. Since 1984, six large pressurized water reactor units have been isolated in France and South Africa[1,2]. At the Cruas plant in France, where the site safe shutdown earthquake (SSE) acceleration was 0.2g, four units were constructed on base isolation devices. Each of the four units is supported on 1,800 neoprene pads. At the Koeberg nuclear power station in South Africa, where the site SSE acceleration was 0.3g, two units were isolated. A total of 2,000 neoprene pads with friction plates were used.

The most important advantage of base isolation applications in nuclear power plants is that the safety and reliability of the plants can be remarkably improved through a standardization of the structures and equipment regardless of the seismic conditions of the sites. The standardization of structures and equipment will reduce the capital cost and design/construction schedule for future plants. Also, a base isolation can facilitate in a decoupling of the design and development for equipment, piping, and components due to the use of the generic in-structure response spectra associated with a standardized plant. Moreover, a base isolation will improve the plant safety margin against the design basis earthquake as well as a beyond design basis seismic event due to its superior seismic performance. Base isolation of individual components is especially beneficial in a situation where existing components and their supports have to be requalified for higher seismic loads. By using a base isolation, it may be possible to avoid an expensive retrofitting of the supporting facility and foundation.

Recent studies have shown that the use of base isolation devices instead of anchor bolts for an Emergency Diesel Generator (EDG) can remarkably increase the seismic resistance of the EDG and finally reduce the core damage frequency in a nuclear power plant[3,4]. For a base isolation of rotating equipment such as an EDG, specially, a coil spring-viscous damper system is suitable because a mechanical vibration in a vertical direction is generated during an operation and it is reduced by a coil spring with a low vertical stiffness. Thus, a coil spring-viscous damper system has been adapted to vibrating machines to reduce their mechanical vibration during an operation as well as the seismic force during an earthquake[5-7]. This study demonstrates the effectiveness of a coil spring-viscous damper system for a vibration and seismic isolation of EDG sets through a measurement of their operational vibration and seismic responses.

SPRING-VISCOUS DAMPER SYSTEM

A helical spring-viscous damper system is a well-known isolation device to effectively reduce structural and mechanical vibrations as well as seismic response in highly seismic areas. The system is suitable for a vibration isolation of structures especially against the vertical motions of mechanical vibrations or earthquakes. The helical springs support the weight of the structure and allow its motion in all three directions by their low horizontal and vertical stiffnesses. Steel helical springs are very adequate for a vibration isolation since the ratio between their vertical and horizontal stiffnesses is able to be easily varied to meet the required system frequency. Viscous dampers minimize undesirable motions in all possible directions by absorbing earthquake energy. The viscous dampers can provide a sufficient amount of damping, up to 20-30 percent of a critical damping, in all three directions and reduce the response of the structure considerably. Especially, a damping is desirable when passing resonance zones of a system during a start-up and shutdown of rotating equipment.

Viscous dampers consisting of a moving piston immersed in a highly viscous fluid show a behavior that is both elastic and viscous. The piston may move in all directions within the damper housing, thus providing a three-dimensional damping. Their mechanical properties are strongly frequency dependent, i.e., high damping in the lower frequency range of system resonances and earthquake motions but a negligible damping only in the operational speed range of the equipment as shown in Figure 1.

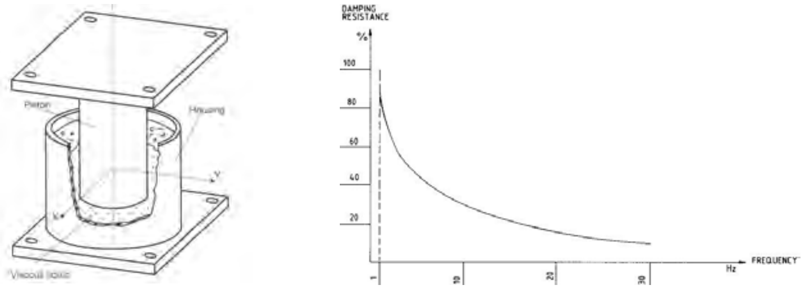


Fig. 1 Typical viscous damper and frequency dependency of damping resistance[7,8]

The reaction of viscous dampers is mainly velocity proportional. Slow motion of the piston, for example from a heat expansion in the supported system, leads to nearly no resistance, but in the case of a short pulse or random excitation with a high velocity, the damper will react with a high resistance. Thus, the helical spring-viscous damper isolation systems are capable of providing an effective isolation for both seismic and mechanical vibrations.

EFFECTIVENESS FOR A VIBRATION ISOLATION

The effectiveness of a coil spring-viscous damper system for a vibration isolation of an EDG was demonstrated through a measurement of its vibration during an operation. The vibration measurement for an identical EDG set with different base systems - one with an anchor bolt system and the other with a coil spring-viscous damper system - was conducted. The engine unit of an EDG set to be measured is a model 16PC2-5V 400 (7,650 kW at 514 rpm) manufactured by HANJUNG-SEMT Pielstick. The EDG set is installed on a concrete foundation with anchor bolts (anchor bolt system) at Yonggwang Nuclear Unit 5, while mounted on 20 coil spring units and 6 viscous dampers (spring-damper system) at Ulchin Nuclear Unit 3 of Korea.

Spring Damper System for an Emergency Diesel Generator

The EDG set of Ulchin Nuclear Unit 3 is mounted on a spring-damper system in order to prevent a transfer of an operational vibration from the EDG body to the floor of the building. A spring unit consists of 8 coil spring elements, and has a vertical stiffness of 3.56 kN/mm and a horizontal stiffness of 2.49 kN/mm as shown in Figure 2. A spring unit has a

Item		Properties
Load Capacity		178 kN
Height		405 mm
Stiffness	Vertical	3.56 kN/mm
	Horizontal	2.49 kN/mm
Damping Coefficient	Vertical	250 kNs/m
	Horizontal	250 kNs/m

Fig. 2 Spring-damper system for the EDG set

ratio of the horizontal stiffness to the vertical stiffness of 0.7. A viscous damper has a damping coefficient of 2.50 kNs/m in both the vertical and horizontal directions as shown in Figure 2.

Vibration Measurement

As described before, an identical EDG set is installed on a different base system at two different nuclear power plants: one is on the anchor bolt system and the other is on the spring-damper system. The vibration was measured by using 8 PCB Piezotronics model 393B12 accelerometers, whose locations are shown in Figures 3 and 4, during both a non-operation condition and a normal operation condition of the engine for a comparison. For the anchor bolt system, 6 accelerometers (P1-P6) were installed on the surface of the EDG concrete foundation separated from the floor slab, one (P7) was installed on the engine, and one (P8) was installed on the concrete floor slab as shown in Figure 3. For the anchor bolt system, 6 accelerometers (P1-P6) were installed on the steel frame which supports the EDG, one (P7) was installed on the engine, and one (P8) was installed on the concrete floor slab.

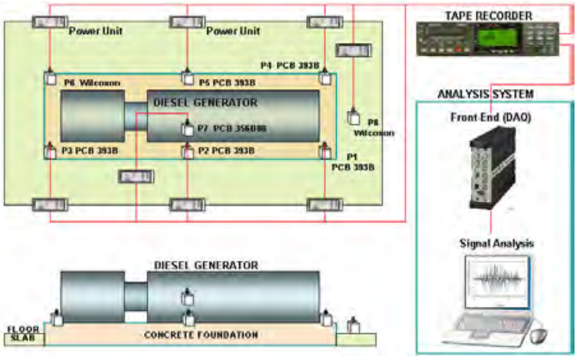


Fig. 3 Vibration measurement system for the anchor bolt system

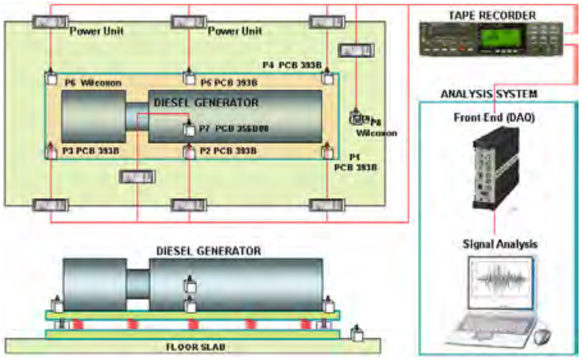


Fig. 4 Vibration measurement system for the spring-damper system

Acceleration Responses

The accelerations measured from the EDG with the anchor bolt system and the spring-damper system during both a non-operation condition and a normal operation condition of the engine are shown in Tables 1 and 2. For the EDG with the anchor bolt system, the average accelerations measured on the concrete foundation (P1-P6) are 0.005 m/s^2 or 53.0 dB under a non-operation condition and 0.166 m/s^2 or 84.0 dB under a normal operation condition. Accelerations on the engine unit (P7) were recorded as 0.183 m/s^2 or 85.2 dB under a non-operation condition and as 1.056 m/s^2 or 100.5 dB under a normal operation condition, and the accelerations on the floor slab (P8) were recorded as 0.003 m/s^2 or 48.0 dB under a non-operation condition and as 0.071 m/s^2 or 77.1 dB under a normal operation condition. A larger acceleration was measured on the engine unit than on the concrete foundation and floor slab. Under a normal operation condition, about 84 and 77 percent of the acceleration on the engine unit was measured on the concrete foundation and floor slab, respectively. There was an 18 percent increase of the acceleration on the engine unit under the normal operation condition, while there was a 60 percent increase of the acceleration on the concrete foundation and floor slab under the normal operation condition. This means that much of the vibration of the engine unit is transmitted to the concrete foundation and floor slab. Considering the accelerations under the non-operation condition, the increase of the acceleration on the floor slab reaches 190 percent.

For the EDG with the spring-damper system, the average accelerations measured on the steel frame (P1-P6) are 0.024 m/s^2 or 67.5 dB under a non-operation condition and 4.262 m/s^2 or 112.2 dB under a normal operation condition. This significant increase on the steel frame is due to the spring-damper system which supports the EDG set and the steel frame. Accelerations on the engine unit (P7) were recorded as 0.036 m/s^2 or 71.1 dB under a non-operation condition and 1.997 m/s^2 or 106.0 dB under a normal operation condition, and the accelerations on the floor slab (P8) were recorded as 0.008 m/s^2 or 58.2 dB under a non-operation condition and 0.048 m/s^2 or 73.7 dB under a normal operation condition. The increase of the accelerations on the engine unit and the floor slab is not significant when compared to the increase for the anchor bolt system. Under a normal operation condition, about 106 and 70 percent of the acceleration on the engine unit were measured on the steel frame and floor slab, respectively. There was a 49 percent increase of the acceleration on the engine unit under the normal operation condition, while there were 66 and 27 percent increases of the acceleration on the steel frame and floor slab under the normal operation condition, respectively. This means that when the engine is in the normal operation, the vibration of the steel frame will be increased by the base isolation system, while the vibration transmitted to the floor slab will be reduced significantly. Considering the accelerations under the non-operation condition, the decrease of the acceleration on the floor slab reaches 44 percent. After all, the reduction of the transmitted acceleration to the floor slab from the engine unit reaches about 80 percent for the spring-damper system when considering the increase on the floor slab for the anchor bolt system.

Figure 5 shows the vibration records measured on the EDG engine unit (P7), the EDG foundation (P1), and the floor slab (P8) for the anchor bolt system during a normal operation condition of the engine. It is found that the vibration amplitude on the EDG foundation is smaller than that on the EDG engine, and the vibration amplitude on the floor slab is smaller than that on the foundation because a direct transmission of a vibration is prevented by the gap between the concrete foundation of the EDG set and the floor slab of the building. The vibration of the EDG foundation may be transmitted to the floor slab through the subsoil and the building foundation. Thus, the gap between the foundation of the EDG set and the floor slab of the building more or less has an isolation effect on the EDG set. Figure 6 shows the vibration records measured on the EDG engine unit (P7), the steel frame (P1), and the floor slab (P8) for the spring-damper system during a normal operation condition of the engine. It is found that the vibration amplitude on the steel frame is significant but the vibration amplitude on the floor slab is negligible because much of the vibration on the steel frame is thoroughly isolated by the spring-damper system. This figure demonstrates the effectiveness of the spring-damper system in isolating a mechanical vibration of rotating machines.

Table 1. Vibration measurement for the anchor bolt system

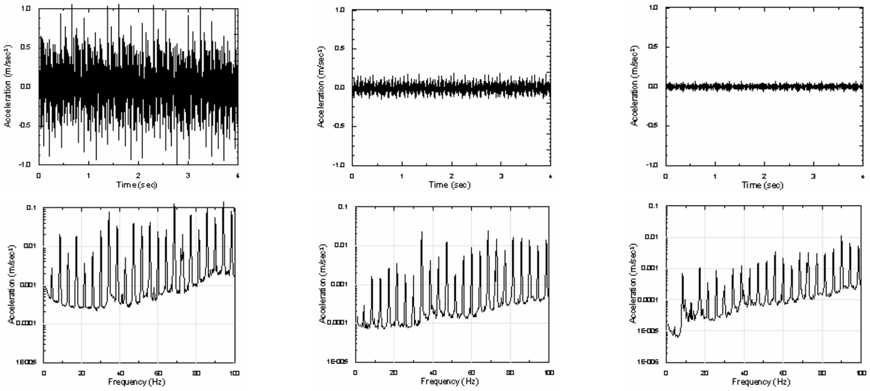
Measuring Location	Non-Operation				Normal Operation			
	Time Domain		Frequency Domain		Time Domain		Frequency Domain	
	Peak (m/s^2)	Peak* (dB)	OA (m/s^2)	OA* (dB)	Peak (m/s^2)	Peak* (dB)	OA (m/s^2)	OA* (dB)
P1	0.004	52.5	0.0009	39.3	0.187	85.4	0.0672	76.6
P2	0.004	51.3	0.0007	37.4	0.140	82.9	0.0543	74.7
P3	0.006	55.1	0.0011	41.4	0.117	81.4	0.0421	72.5
P4	0.006	56.0	0.0013	42.6	0.269	88.6	0.0880	78.9
P5	0.003	50.0	0.0005	35.1	0.147	83.4	0.0506	74.1
P6	0.005	54.0	0.0009	39.5	0.133	82.5	0.0467	73.4
P7	0.183	85.2	0.0403	72.1	1.056	100.5	0.3619	91.2
P8	0.003	48.0	0.0005	34.8	0.071	77.1	0.0214	66.6

*Reference amplitude = 1×10^{-5}

Table 2. Vibration measurement for the spring-damper system

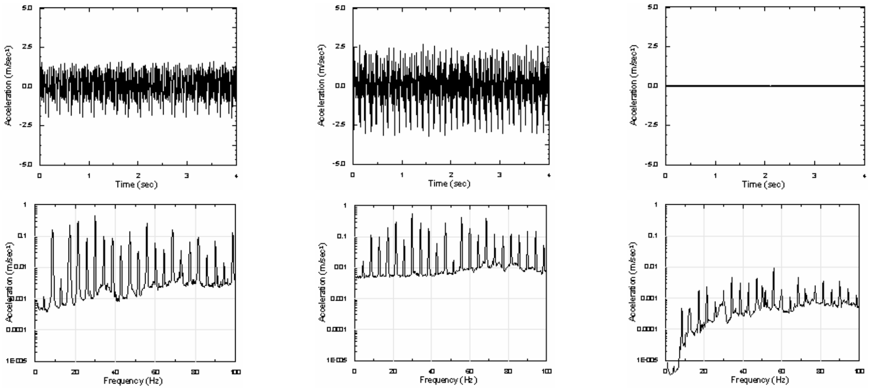
Measuring Location	Non-Operation				Normal Operation			
	Time Domain		Frequency Domain		Time Domain		Frequency Domain	
	Peak (m/s^2)	Peak* (dB)	OA (m/s^2)	OA* (dB)	Peak (m/s^2)	Peak* (dB)	OA (m/s^2)	OA* (dB)
P1	0.023	67.3	0.0051	54.2	3.202	110.1	1.3599	102.7
P2	0.024	67.7	0.0042	52.6	2.879	109.2	1.3480	102.6
P3	0.031	69.7	0.0075	57.6	6.242	115.9	3.0339	109.6
P4	0.023	67.2	0.0057	55.2	4.807	113.6	2.0520	106.2
P5	0.017	64.6	0.0050	54.1	3.072	109.7	1.3192	102.4
P6	0.027	68.7	0.0055	54.9	5.367	114.6	2.0278	106.1
P7	0.036	71.1	0.0033	50.4	1.997	106.0	0.9339	99.4
P8	0.008	58.2	0.0033	50.5	0.048	73.7	0.0218	66.8

*Reference amplitude = 1×10^{-5}



(a) Engine unit (P7) (b) Foundation (P1) (c) Floor slab (P8)

Fig. 5 Vibration records for the anchor bolt system



(a) Engine unit (P7) (b) Steel frame (P1) (c) Floor slab (P8)

Fig. 6 Vibration records for the spring-damper system

EFFECTIVENESS FOR A SEISMIC ISOLATION

The seismic effectiveness of a coil spring-viscous damper system was demonstrated by seismic tests of the scaled model of a base-isolated EDG on a shaking table. As a prototype, an EDG set with a HANJUNG-SEMT Pielstick Engine 16PC2-5V 400 was chosen, which is identical to the EDG installed at Yonggwang Nuclear Unit 5 and Ulchin Nuclear Unit 3 of Korea, and the scaled model was designed to represent the seismic behavior of a prototype of the EDG set. Concrete and steel blocks were used to build an EDG model, and a coil spring-viscous damper system was used as a base isolation system. The dynamic characteristics of the coil spring-viscous damper system were obtained by cyclic tests and the seismic responses of the base-isolated EDG model were obtained by shaking table tests.

Test Model

The prototype of the EDG set consists of an engine unit, a generator unit, and a concrete mass. Net weights of the engine unit, the generator unit, and the concrete mass are 912 kN, 392 kN, and 2,474 kN, respectively, and the total weight is 3,779 kN. A 6-DOF seismic simulator with a table dimension of 2.5 m × 2.5 m was used for the model test. Test model was designed by considering the size of the shaking table of the simulator as shown in Figure 7, which consists of a concrete block of 2,300 mm × 800 mm × 450 mm, four steel blocks of 600 mm × 600 mm × 140 mm, and two steel plates of 1,500 mm × 300 mm × 30 mm. Total weight of the test model is 39 kN and the steel blocks were placed to have an equivalent mass center of the prototype.

Spring Damper System for Test Model

For the seismic isolation of the EDG test model, a spring-damper unit that consists of a combination of 2 coil springs and one viscous damper was adapted as shown in Figure 8. The stiffnesses and the damping coefficients of the spring-damper unit for the vertical and horizontal directions were determined by the seismic responses of the EDG test model for the input motion. The test model was supported by 4 spring-damper units as shown in Figure 7.

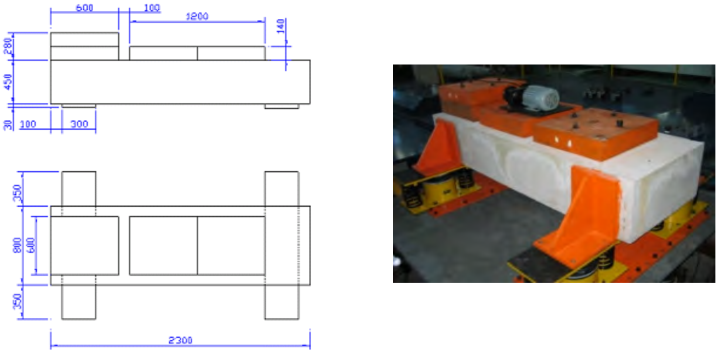


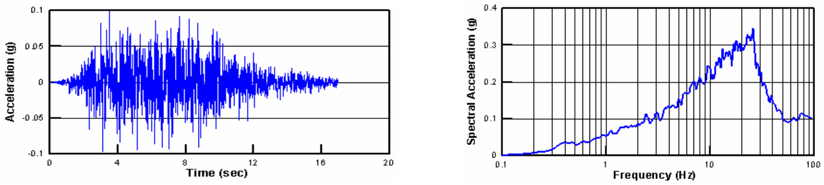
Fig. 7 EDG test model for table tests

Item		Properties
Load Capacity		15 kN
Height		410 mm
Stiffness	Vertical	0.144 kN/mm
	Horizontal	0.04 kN/mm
Damping Coefficient	Vertical	3.5 kNs/m
	Horizontal	4.0 kNs/m

Fig. 8 Spring-damper unit for the EDG test model

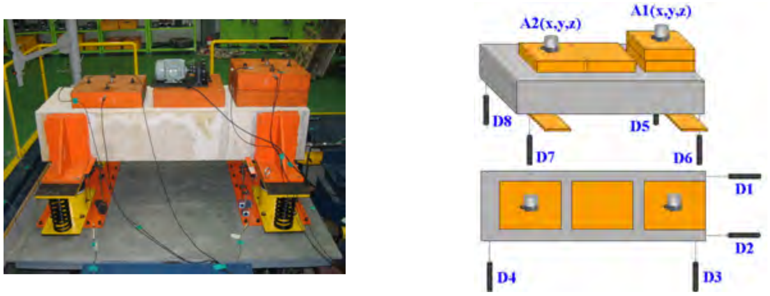
Shaking Table Test

Seismic tests were carried out for one and three directional excitations with three peak acceleration levels of 0.1g, 0.2g, and 0.3g. An artificial time-history corresponding to the scenario earthquake for a Korean nuclear site was used as a table input motion. Identical input motions and peak acceleration levels were used in the horizontal and vertical directions. Figure 9 shows the artificial time history and response spectrum of the input motion. The acceleration and displacement responses were measured by using two accelerometers (A1 & A2) and eight LVDTs (D1-D8) as shown in Figure 10.



(a) Artificial time-history (b) Response spectrum

Fig. 9 Input motion for the shaking table tests



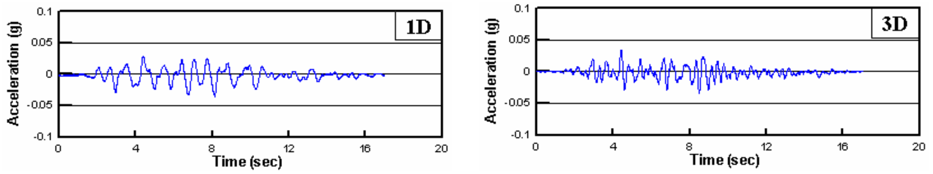
(a) EDG test model (b) Accelerometers and LVDTs

Fig. 10 Test model and measurement systems for the shaking table test

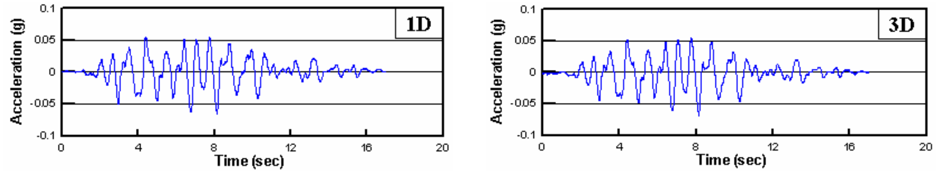
Seismic Responses

Figures 11 and 12 show the acceleration responses obtained from accelerometer A1 for the peak acceleration levels of 0.1g, 0.2g, and 0.3g during the one and three directional excitations and the spectral accelerations for the peak acceleration level of 0.2g, respectively. Figure 11 shows that the acceleration responses on the EDG model are reduced significantly by the spring-damper system. There is little difference between the acceleration responses in the one horizontal excitation and those in the three directional excitations. Figure 12 shows that identical spectral accelerations are obtained from accelerometers A1 and A2 in both the one horizontal excitation and the three directional excitations, and the predominant frequency shift to 1.3Hz from 23.5Hz. Thus, the spectral accelerations decrease significantly. The differences between the acceleration responses in the one horizontal excitation and the three directional excitations are very small.

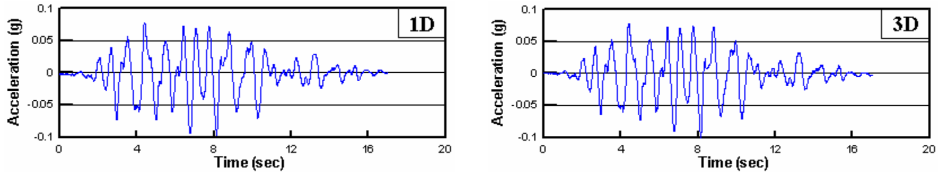
The seismic effectiveness of the coil spring-viscous damper system was evaluated by the ratio of the maximum acceleration response for the model to the table acceleration as arranged in Table 3. The average response ratios for the one horizontal excitation, the horizontal and vertical directions for three excitations are 0.283, 0.305, and 0.558, respectively. This indicates that the spring-damper system reduces the seismic force transmitted to the EDG model from the table by



(a) Peak acceleration of 0.1g

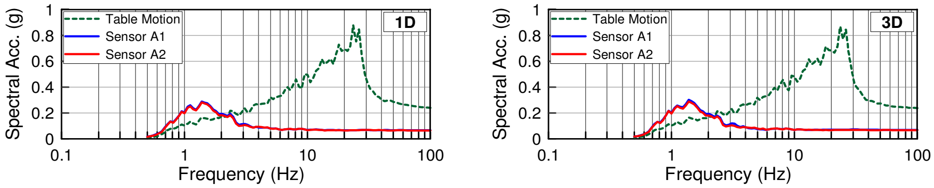


(b) Peak acceleration of 0.2g



(c) Peak acceleration of 0.3g

Fig. 11 Acceleration responses for different peak accelerations at accelerometer A1



(a) One horizontal excitation (b) Three directional excitations

Fig. 12 Spectral accelerations for peak acceleration of 0.2g

Table 3. Acceleration response ratios for the isolated EDG test model

Target	1D-Horizontal			3D-Horizontal			3D-Vertical		
PGA (g)	Table (g)	Model (g)	Ratio	Table (g)	Model (g)	Ratio	Table (g)	Model (g)	Ratio
0.1	0.118	0.035	0.297	0.110	0.037	0.336	0.062	0.034	0.548
0.2	0.242	0.066	0.273	0.238	0.070	0.294	0.127	0.072	0.567
0.3	0.353	0.098	0.278	0.354	0.101	0.285	0.181	0.101	0.558

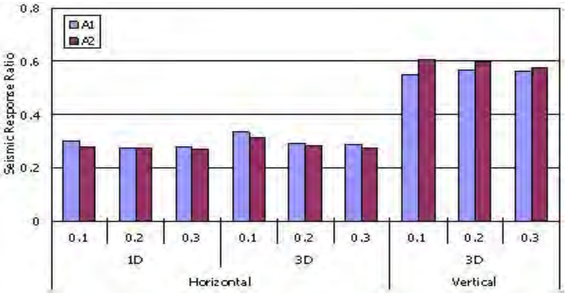


Fig. 13 Comparisons of acceleration response ratios for the isolated EDG test model

up to around 70 percent in the horizontal direction and 45 percent in the vertical direction, respectively. These acceleration response ratios for different acceleration levels are also shown in Figure 13. It is easily seen that the spring-damper system is an effective isolation device for the EDG.

CONCLUSION

The effectiveness of a coil spring-viscous damper system as a vibration and seismic isolation system for an EDG was evaluated in this study. The effectiveness of a coil spring-viscous damper system for a vibration isolation of the EDG was evaluated through a measurement of its vibration during an operation. The vibration measurement for an identical EDG set with different base systems - one with an anchor bolt system and the other with a coil spring-viscous damper system - was conducted. The acceleration responses for the anchor bolt system and the spring-damper system during a non-operation condition and a normal operation condition of the EDG engine showed that the spring-damper system reduces the acceleration amplitude transmitted to the building floor slab from the EDG engine unit by more than 80 percent.

The seismic effectiveness of a coil spring-viscous damper system was evaluated by seismic tests with a scaled model of a base-isolated EDG on a shaking table. The scaled model was designed to represent the seismic behavior of a prototype of the EDG set. The seismic responses of the base-isolated EDG model obtained by the shaking table showed that the spring-viscous damper system could reduce the seismic force transmitted to the EDG by up to 70 percent.

It was demonstrated that a spring-viscous damper is an effective vibration and seismic isolation system for an EDG in nuclear power plants through an evaluation of its vibration and seismic isolation effectiveness. A coil spring-viscous damper system is suitable for vibrating machines to reduce both the transmission of their mechanical vibrations to a floor during an operation and the transmission of a seismic force to them during an earthquake.

ACKNOWLEDGEMENT

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