A PERFORMANCE ASSESSMENT OF A BASE ISOLATION SYSTEM FOR AN EMERGENCY DIESEL GENERATOR IN A NUCLEAR POWER PLANT

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This study evaluates the performance of a coil spring-viscous damper system for the vibration and seismic isolation of an Emergency Diesel Generator (EDG) by measuring its operational vibration and seismic responses. The vibration performance of a coil spring-viscous damper system was evaluated by the vibration measurements 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. The seismic performance of the coil spring-viscous damper system was evaluated by seismic tests with a scaled model of a base-isolated EDG on a shaking table. The effects of EDG base isolation on the fragility curve and core damage frequency in a nuclear power plant were also investigated through a case study.

KEYWORDS : Emergency Diesel Generator, Coil Spring-Viscous Damper, Vibration Isolation, Seismic Isolation, Seismic Fragility, Core Damage Frequency

1. INTRODUCTION

An Emergency Diesel Generator (EDG) is the primary power source, supplying AC power to the Class 1E power systems and equipment when the main turbine generator and offsite power source are not available in nuclear power stations. The EDG reduces the probability of a station blackout (SBO) due to AC power failure, and finally it reduces the core damage frequency. Thus, the performance of an EDG will be very important to sustain the long-term safety of a nuclear power plant.

For the purpose of improving the integrity of an EDG set, a spring-damper system has been adopted as a base isolation system because it is able to reduce the mechanical vibration level on the floor during the operation of an engine as well as the seismic force transmitted to an EDG body from the ground during an earthquake. 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 the 1970s. Some of them, for example rubber bearings and friction systems, have been widely adopted for buildings and civil structures such as bridges in several countries of a high seismicity, and their effectiveness has been demonstrated through surviving strong earthquakes such as the 1994 Northridge and 1995 Kobe Earthquakes [1,2,3].

In spite of the many advantages of a base isolation, however, the applications of a base isolation to nuclear facilities have been very limited to date because of a lack of sufficient data for the long-term operation of such isolation devices. Since 1984, six large pressurized water reactor units have been isolated in France and South Africa [4,5]. Moreover, there are a limited number of studies on the seismic isolation of equipment and components in spite of the potential advantages that the application of a base isolation system for equipment and components could improve the seismic safety of nuclear power plants. Kelly [6], Hall [7], and Ebisawa et al. [8] proposed the use of base isolation systems to improve the seismic capacity of various components. The results of their studies indicate that the use of a base isolation in light secondary equipment or a large component can be beneficial in reducing the accelerations experienced by a component. Ebisawa et al. [8] studied the base isolation of a nuclear component by experimental and numerical methods and developed a technical basis for a seismic isolation of nuclear components. They also carried out various experiments including field tests against real earthquakes in order to obtain test data for a component base isolation. They concluded in their study that a seismic base isolation can improve the seismic resistance of nuclear components and decrease their functional failure probability. Huang et al. [9] showed that considerable reductions in the seismic demands on secondary systems in a nuclear power plant can be realized by using seismic isolation systems.

Recent studies have shown that the use of base isolation devices instead of anchor bolts for an EDG can remarkably increase the seismic resistance of an EDG and finally reduce the core damage frequency in a nuclear power plant [10,11]. For a base isolation of rotating equipment such as an EDG, a coil spring-viscous damper system is especially suitable because a mechanical vibration in a vertical direction is generated during its operation and it is reduced by a coil spring with a low vertical stiffness. Thus, a coil spring-viscous damper system has been used in vibrating machines to reduce their mechanical vibration during operations as well as the seismic force during an earthquake [12,13,14,15]. Tezcan and Civi [16] demonstrated the base isolation efficiency of a coil spring-viscous damper system through shaking table tests, and actually a significant reduction of the peak acceleration at the superstructure supported by coil steel springs and viscoelastic fluid dampers was verified during the Northridge Earthquake of January 17, 1994 [17]. Makris and Constantinou [18] proposed procedures to analyze the dynamic response of structures supported by coil springs and viscous dampers, and their reasonable accuracy in predicting the seismic responses was proven [17]. Their analysis procedures adopted a generalized derivative Maxwell model [19] to represent the dynamic behavior of viscous dampers. Makris et al. [20,21,22,23] developed analytical models of viscous dampers to obtain a reasonable seismic response of structures with a coil spring-viscous damper system.

This study evaluated the performance of a coil spring-viscous damper system for the vibration and seismic isolation of EDG sets by measuring their operational vibration and seismic responses. Also, the effect of base isolation on a seismic fragility curve of an EDG was investigated. Finally, when the base isolation system was introduced to an EDG set, the core damage frequencies were evaluated through a case study.

2. COIL SPRING-VISCOUS DAMPER SYSTEM

A coil 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. This system is suitable for the vibration isolation of structures, especially against the vertical motions of mechanical vibrations or earthquakes. The coil springs support the weight of a structure and allow for its motion in all three directions by their low horizontal and vertical stiffnesses. Steel coil springs are adequate for vibration isolation since the ratio between their vertical and horizontal stiffnesses can be varied easily to meet the required system frequency. Viscous dampers minimize undesirable motions in all possible directions by absorbing an earthquake's energy. These viscous dampers can provide a sufficient amount of damping, up to 20-30% of a critical damping, in all three directions and considerably reduce the response of a structure. A damping is considerably desirable when passing the resonance zones of a system during the start-up and shutdown of rotating equipment.

Viscous dampers, consisting of a moving piston immersed in a highly viscous fluid, exhibit a behavior that is both elastic and viscous. A piston may move in all directions within the damper housing, thus providing a three-dimensional damping. As a result, the mechanical properties of viscous dampers are strongly frequency dependent, i.e., high damping in the lower frequency range of a system's resonances and earthquake motions,

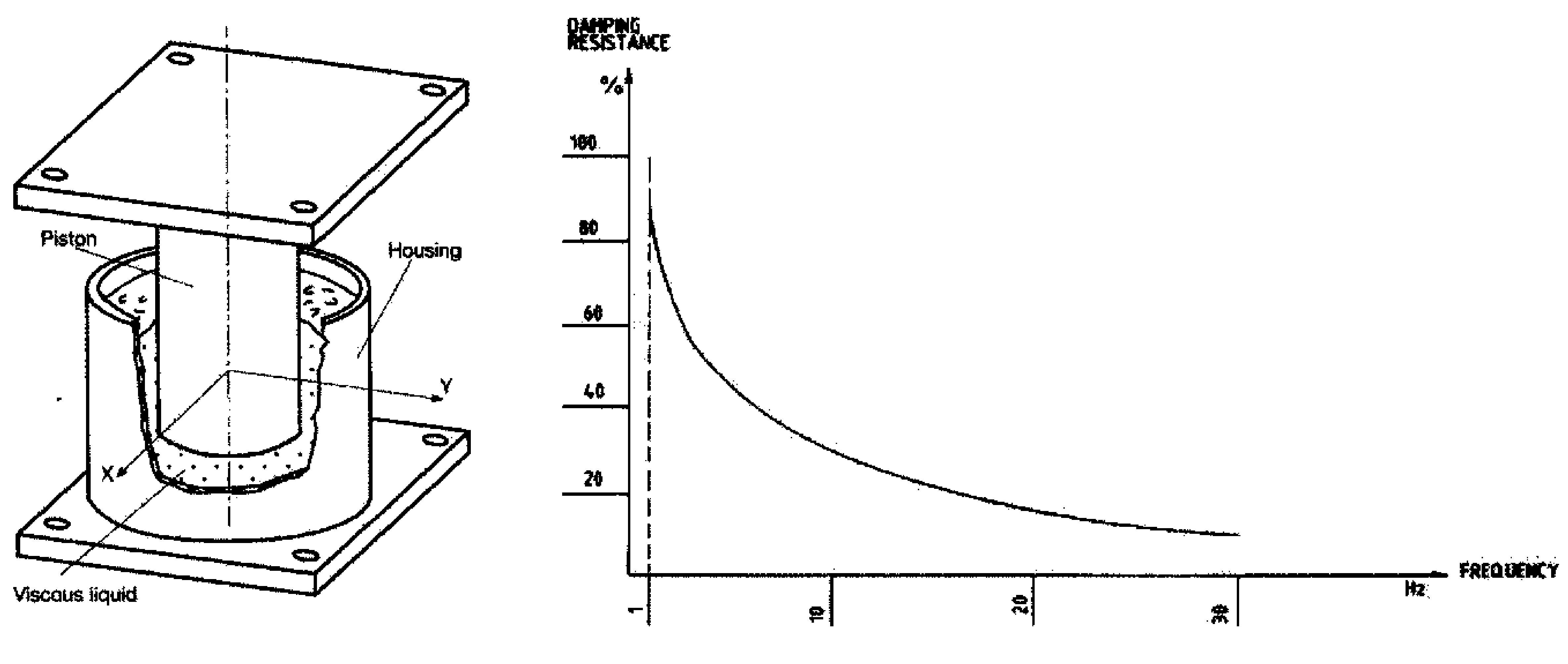


Fig. 1. Typical Viscous Damper and the Frequency Dependency of a Damping Resistance

but only a negligible damping in the operational speed range of the equipment, as shown in Fig. 1 [13, 14].

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

3. PERFORMANCE FOR VIBRATION ISOLATION

The performance of a coil spring-viscous damper system for a vibration isolation of an EDG was demonstrated by measuring 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 Republic of Korea.

3.1 Spring-Damper System for an Emergency Diesel Generator

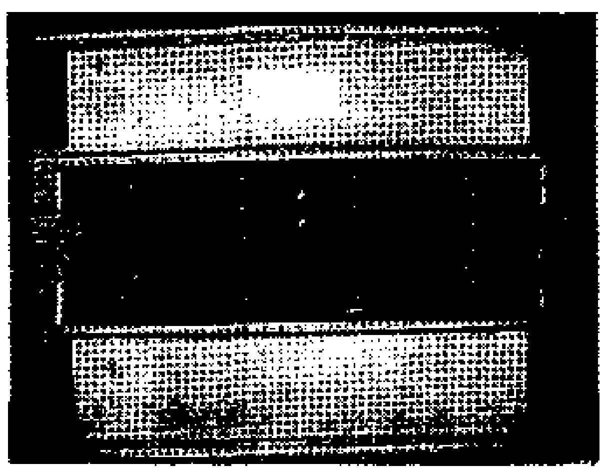
The EDG set of Ulchin Nuclear Unit 3 is mounted on a spring-damper system in order to prevent a transfer of an operational vibration from the EDG body to the floor of the building. A spring unit consists of 8 coil spring elements and has a vertical stiffness of 35.6 N/mm and a horizontal stiffness of 24.9 N/mm, as shown in Fig. 2. A spring unit has a ratio of horizontal stiffness to vertical stiffness of 0.7. A viscous damper has a damping coefficient of 2.5 kNs/m in both the vertical and horizontal directions, as shown in Fig. 2.

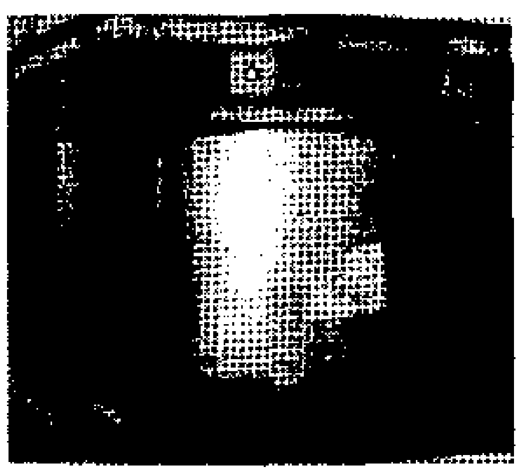
3.2 Vibration Measurement

As described before, an identical EDG set was installed on a different base system at two different nuclear power plants: one was on an anchor bolt system and the other was on a coil spring-viscous damper system. The resultant vibrations were measured by using 8 PCB Piezotronics model 393B12 accelerometers whose locations are shown in Figs. 3 and 4 respectively, during both non-operating and normal operating conditions of the engine for 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 by a gap, one (P7) was installed on the engine, and one (P8) was installed on the concrete floor slab, as shown in Fig. 3. For the spring-damper 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 as shown in Fig. 4.

3.3 Acceleration Responses

The accelerations measured from the EDG with the anchor bolt system and the spring-damper system during both non-operating and normal operating conditions of the engine are shown in Tables 1 and 2, respectively. 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 non-operating conditions and 0.166 m/s^2 or 84.0 dB under normal operating conditions. Accelerations on the engine unit (P7) were recorded as 0.183 m/s^2 or 85.2 dB under non-operating conditions and as 1.056 m/s^2 or 100.5 dB under normal operating conditions, and the accelerations on the floor slab (P8) were recorded as 0.003 m/s^2 or 48.0 dB under non-operating conditions and as 0.071 m/s^2 or 77.1 dB under normal operating conditions, respectively. A larger acceleration was measured





Item		Properties
Load Capacity		178 kN
Height		405 mm
Stiffness	Vertical	35.6 N/mm
	Horizontal	24.9 N/mm
Damping Coefficient	Vertical	2.5 kNs/m
	Horizontal	2.5 kNs/m

Fig. 2. Coil Spring-Viscous Damper System for the EDG Set

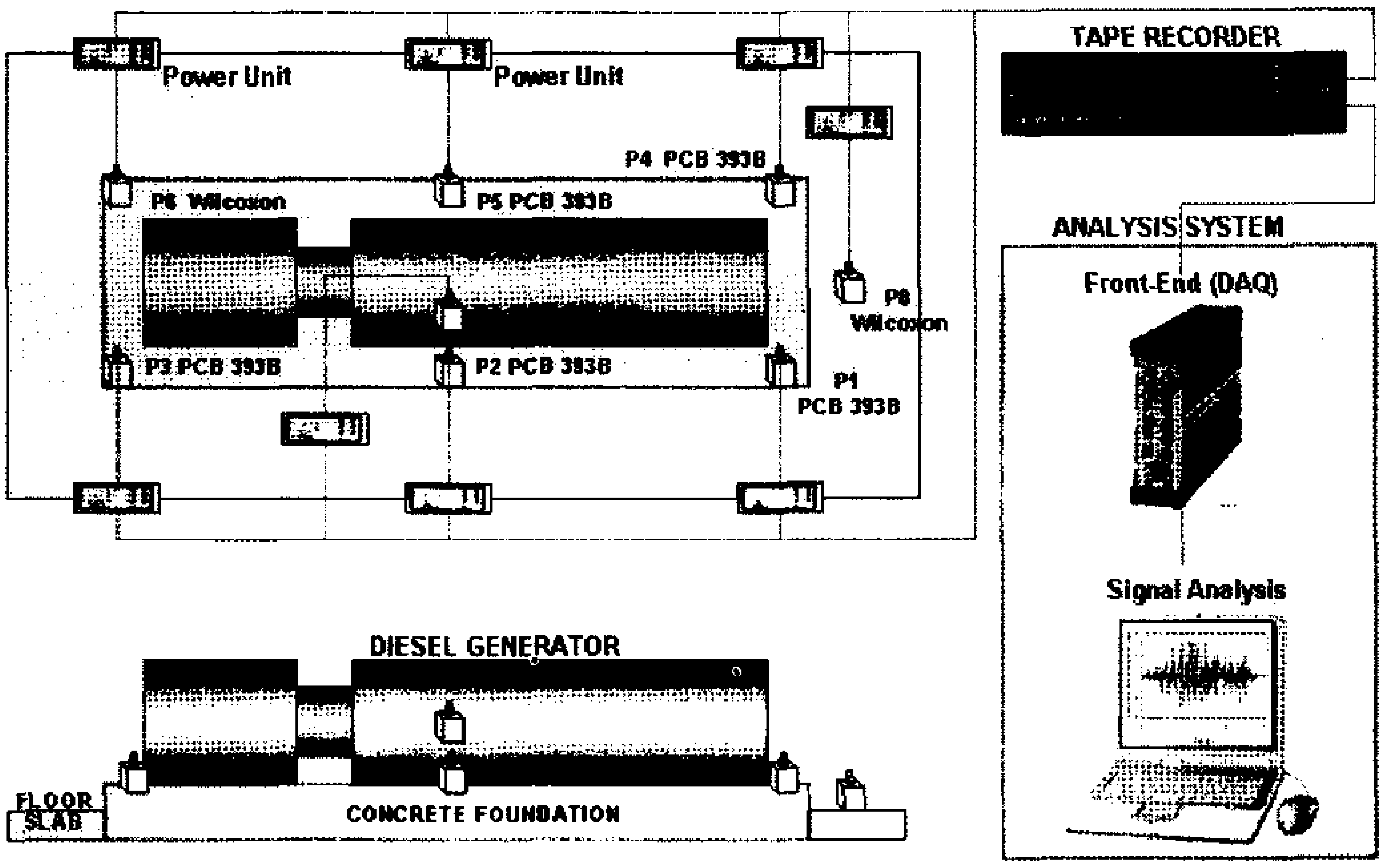


Fig. 3. Vibration Measurement System for the Anchor Bolt System

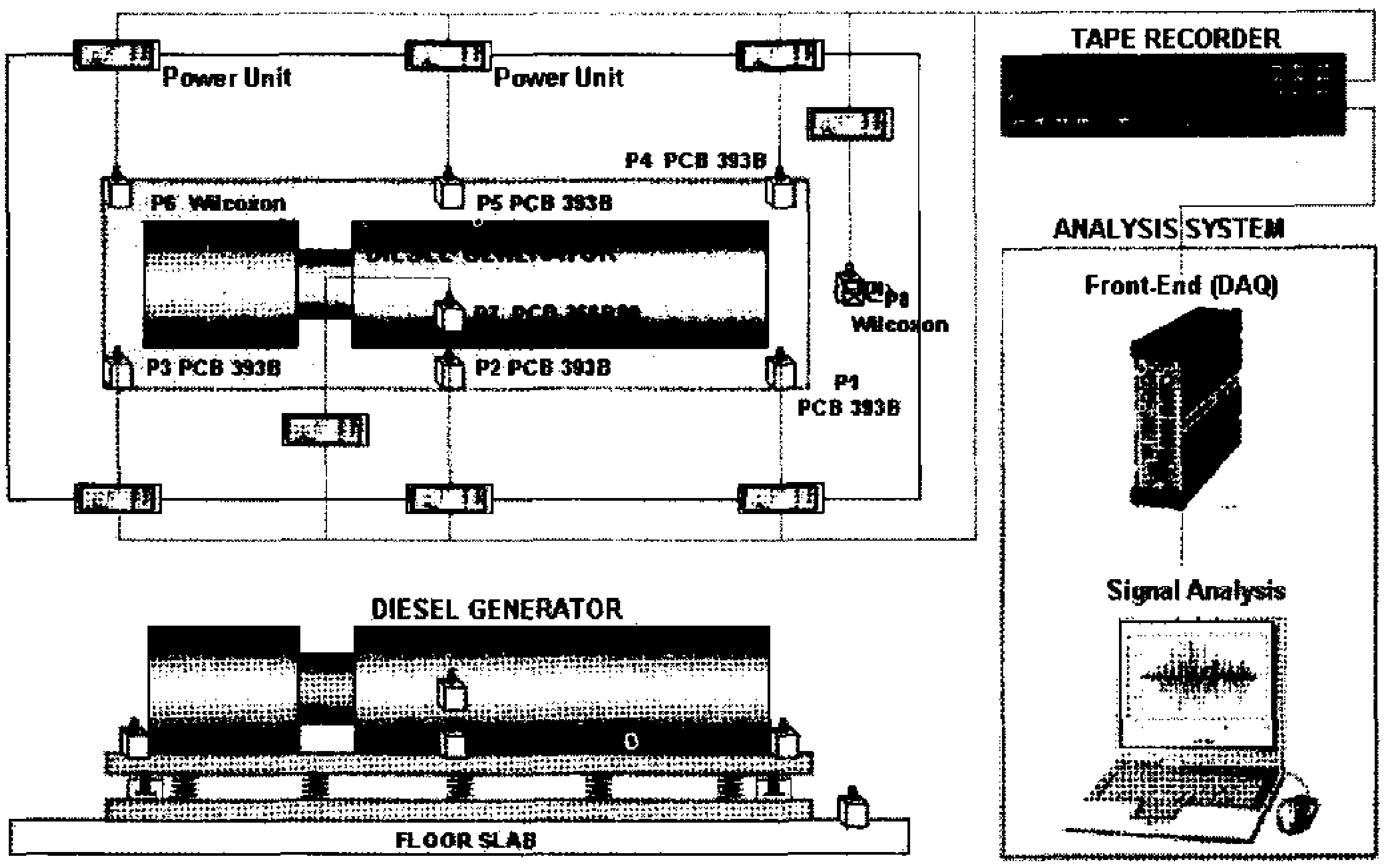


Fig. 4. Vibration Measurement System for the Spring-Damper System

on the engine unit than on the concrete foundation or floor slab. Under normal operating conditions, about 84 and 77% of the acceleration on the engine unit was measured on the concrete foundation and floor slab, respectively. There was an 18% increase of the acceleration on the engine unit under normal operating conditions, while there was a 60% increase of the acceleration on the concrete foundation and floor slab under normal operating conditions. This means that much of the vibration of the engine unit is transmitted to the concrete foundation and floor slab. Considering the accelerations under non-operating conditions, the increase of the acceleration on the floor slab reaches 190%.

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 non-operating conditions and 4.262 m/s^2 or 112.2 dB under normal operating conditions, respectively. This significant increase on the steel frame

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/s²)	Peak* (dB)	OA (m/s²)	OA* (dB)	Peak (m/s²)	Peak* (dB)	OA (m/s²)	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}

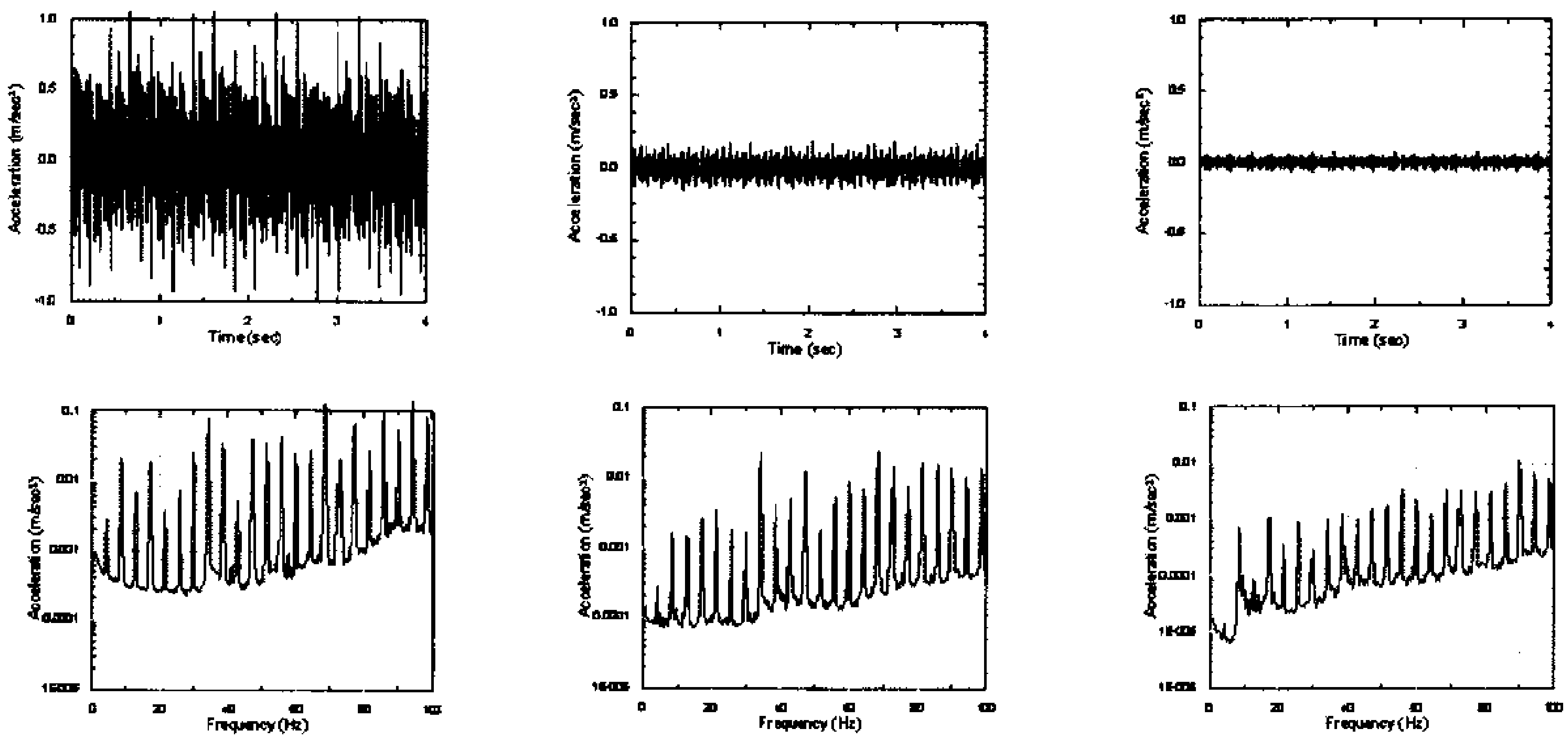
Table 2. Vibration Measurement for the Spring-Damper System

Measuring Location	Non-Operation				Normal Operation			
	Time Domain		Frequency Domain		Time Domain		Frequency Domain	
	Peak (m/s²)	Peak* (dB)	OA (m/s²)	OA* (dB)	Peak (m/s²)	Peak* (dB)	OA (m/s²)	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}

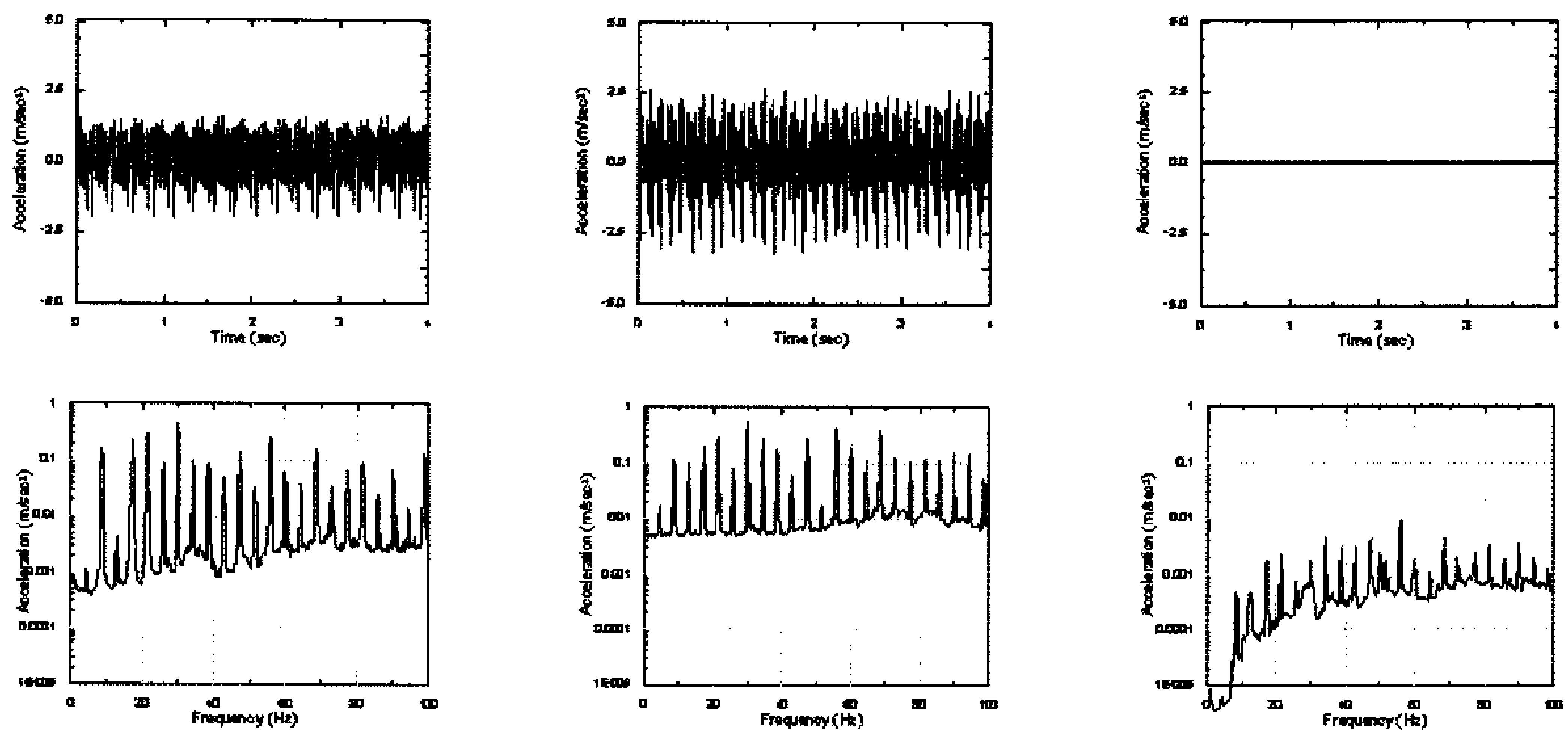
is due to the spring-damper system which supports the EDG set and the steel frame. Accelerations on the engine unit (P7) were recorded as 0.036 m/s² or 71.1 dB under non-operating conditions and 1.997 m/s² or 106.0 dB under normal operating conditions, and the accelerations on the floor slab (P8) were recorded as 0.008 m/s² or 58.2 dB under non-operating conditions and 0.048 m/s² or 73.7 dB under normal operating conditions, respectively. 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 normal operating conditions, about 106 and 70% of the acceleration on the engine unit was measured on the steel frame and floor slab, respectively. There was a 49% increase in the acceleration on the engine unit under normal operating conditions, while there were 66% and 27% increases in the acceleration on the steel frame and floor slab under normal operating conditions, respectively. This means that when the engine is in 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 significantly reduced. Considering the accelerations under non-operating conditions, the decrease of the acceleration on the floor slab reaches 44%. Also, the reduction of the transmitted acceleration to the floor slab from the engine unit reaches about 80% for the spring-damper system when considering the increase on the floor slab for the anchor bolt system.

Fig. 5 shows the vibration records measured for the EDG engine unit (P7), the EDG foundation (P1), and the floor slab (P8) for the anchor bolt system during normal operating conditions 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 has, more or less, an isolation effect on the EDG set. Fig. 6 shows the vibration records measured for the EDG engine unit (P7), the steel frame (P1), and the floor slab (P8) for the spring-damper system during normal operating conditions of the engine. The vibration amplitude on the steel frame was found to be 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 performance of the spring-damper system in isolating a mechanical vibration of rotating machines.



(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

4. PERFORMANCE FOR A SEISMIC ISOLATION

The seismic performance of a coil spring-viscous damper system was demonstrated by seismic tests with a 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 Republic 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.

4.1 Test Model

The prototype of the EDG set consists of an engine unit, a generator unit, and a concrete mass. The 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. The test model was designed by considering the size of the shaking table of the simulator, as shown in Fig. 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. The total weight of the test model is 39 kN, and the steel blocks were placed to produce an equivalent center of mass for the prototype.

4.2 Spring-Damper System for Test Model

A spring-damper unit that consists of a combination of two coil springs and one viscous damper, as shown in Fig. 8, was adopted for the seismic isolation of the EDG test model. At the design stage of the spring-damper unit, 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 design properties of the spring-damper unit are shown in Fig. 8 and the hysteretic force-displacement relationships obtained by cyclic tests and the dynamic properties determined using the hysteretic force-displacement relationships for the spring-damper unit are shown in Figs. 9 and 10, respectively. The EDG

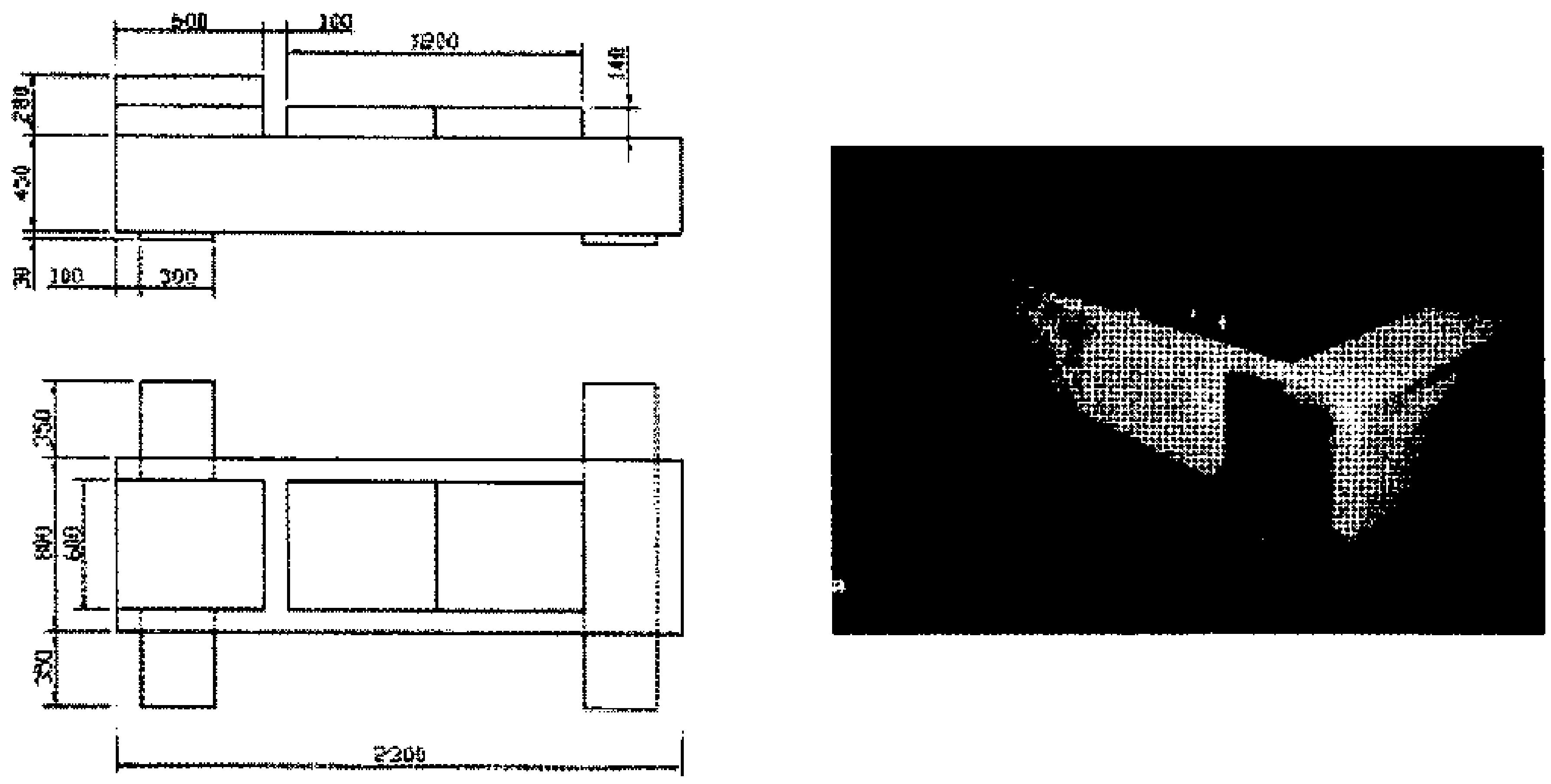
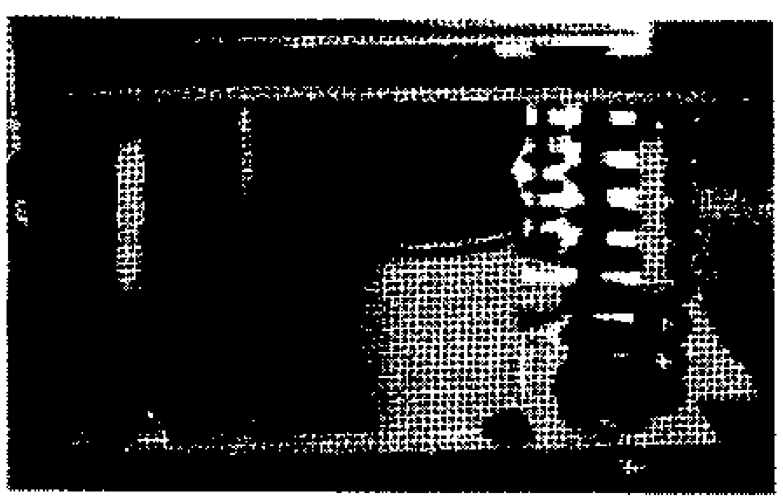


Fig. 7. EDG Test Model for the Seismic Tests



Item		Properties
Load Capacity		15 kN
Height		410 mm
Stiffness	Vertical	144 N/mm
	Horizontal	40 N/mm
Damping Coefficient	Vertical	3.5 kNs/m
	Horizontal	4.0 kNs/m

Fig. 8. Spring-Damper Unit for the EDG Test Model

test model was supported by 4 spring-damper units, as shown in Fig. 7.

4.3 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 [24] 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. Fig. 11 shows the artificial time history and response spectrum of the input motion. The acceleration and displacement responses were measured by using 2 accelerometers (A1 & A2) and 8 LVDTs (D1-D4

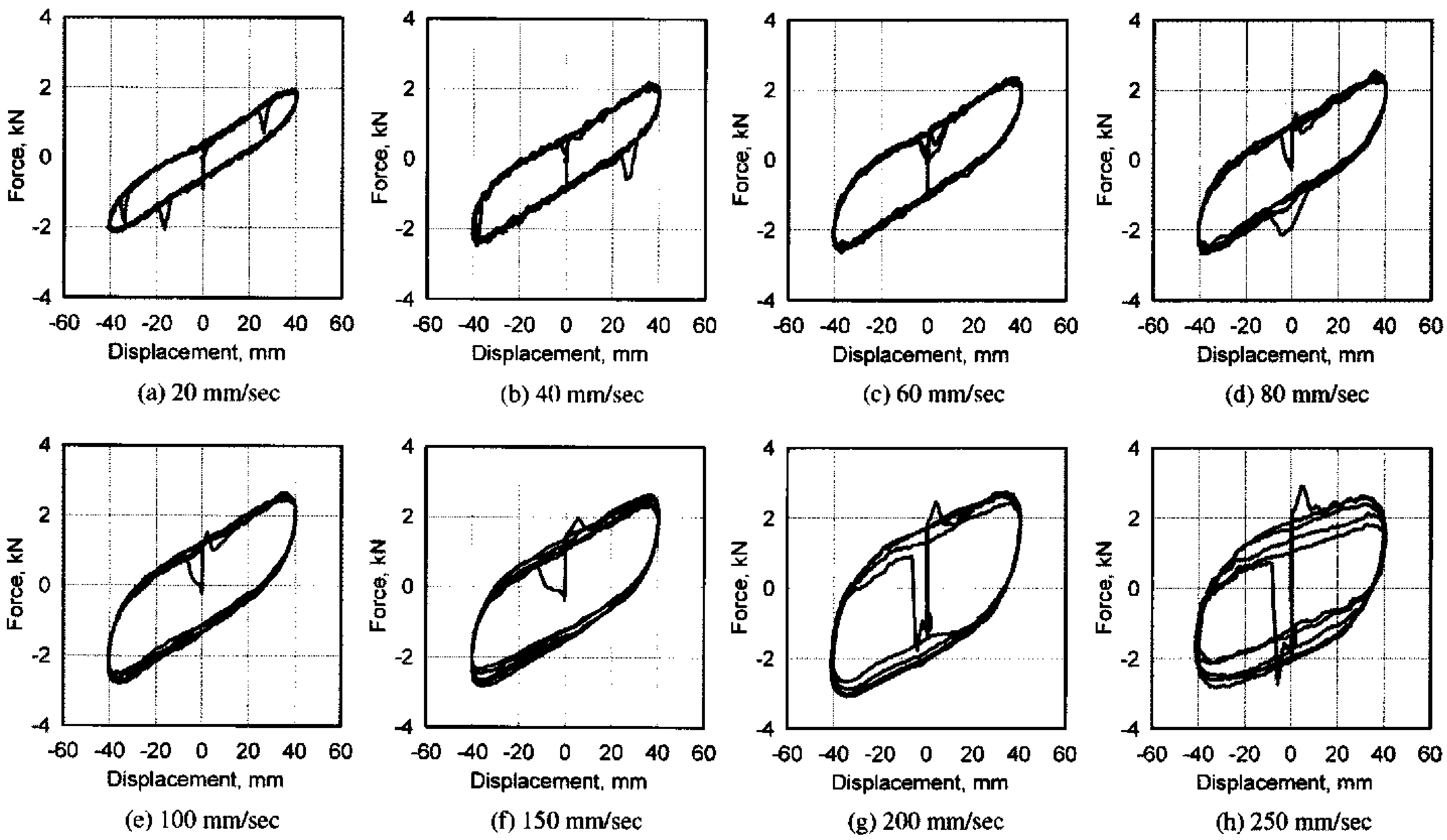


Fig. 9. Hysteretic Force-Displacement Relationships for a Spring-Damper Unit (Transverse)

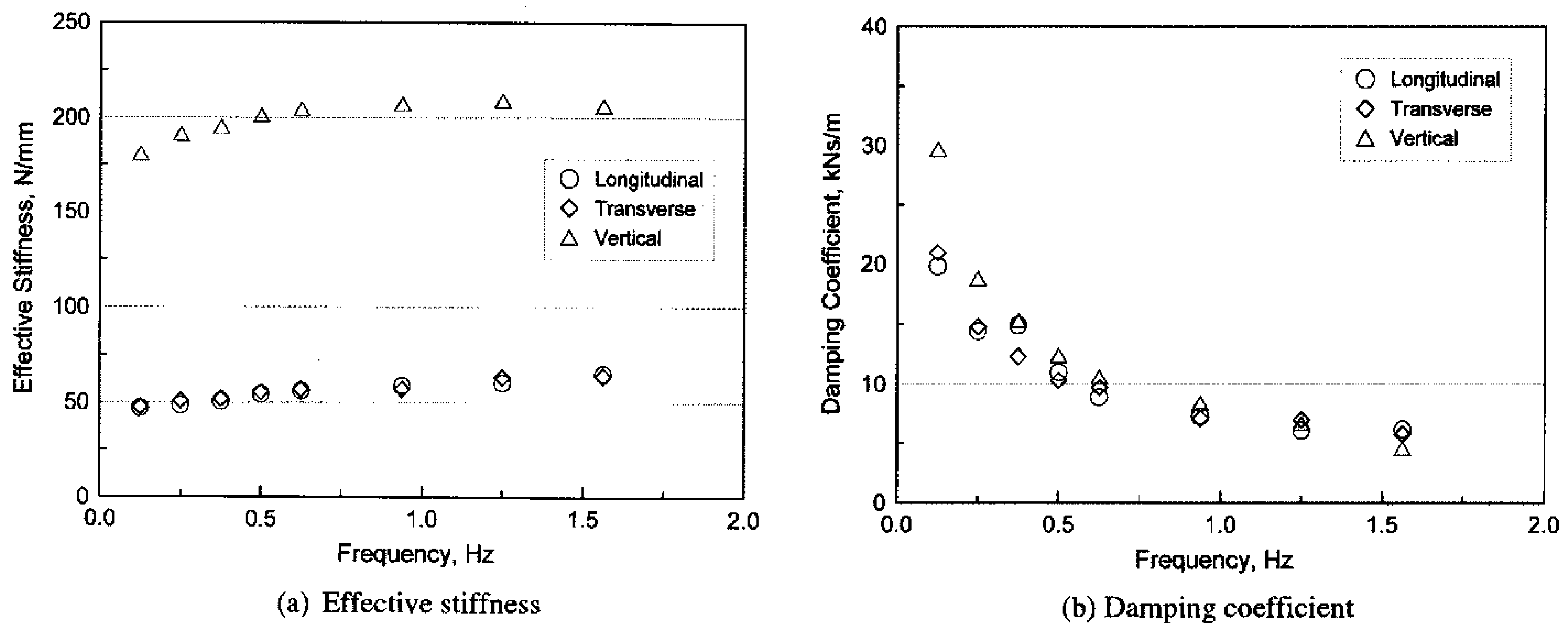


Fig. 10. Dynamic Properties for a Spring-Damper Unit

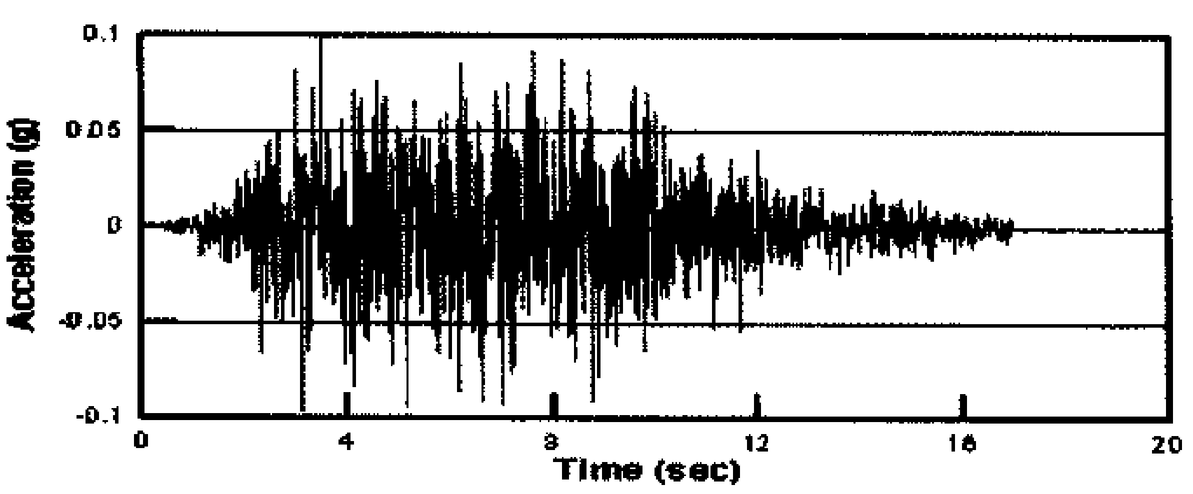
for horizontal; D5-D8 for vertical), as shown in Fig. 12.

4.4 Seismic Responses

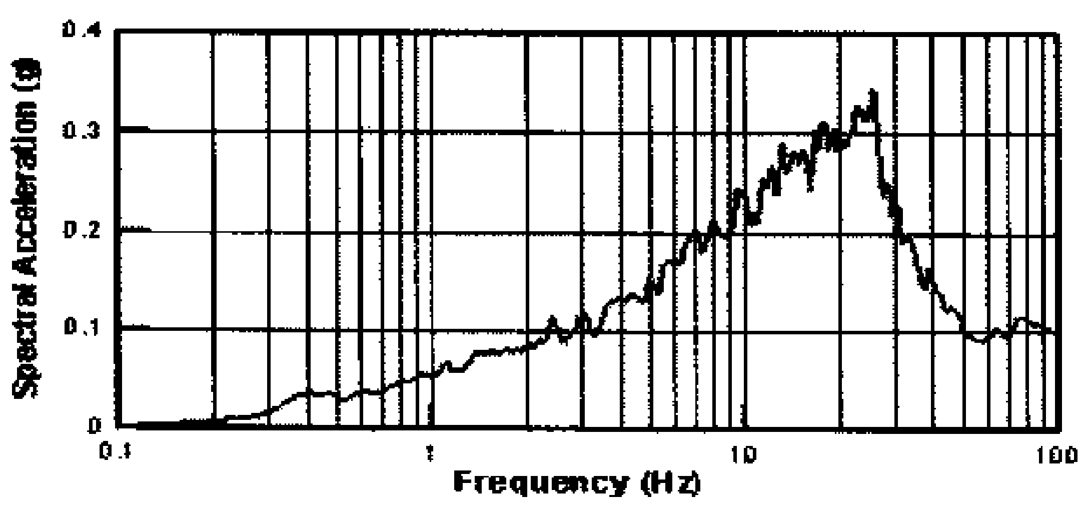
Figs. 13 and 14 show the acceleration responses obtained from accelerometer A1 for the peak acceleration levels of 0.1g, 0.2g, and 0.3g during the one- and three-directional excitations and the spectral accelerations for the peak acceleration level of 0.2g, respectively. Fig. 13 shows that the acceleration responses from the EDG model are reduced significantly by the spring-damper system. There is little difference between the acceleration responses for the one horizontal excitation and those for the three-directional excitations. Fig. 14 shows that identical spectral accelerations are obtained from accelerometers A1 and A2 for both the one horizontal excitation and the three-directional excitations, as well as a predominant frequency shift to 1.3Hz from 23.5Hz. Thus, the spectral accelerations are significantly decreased. The differences between the acceleration responses for the one horizontal excitation and the three-directional excitations are very small.

Figs. 15 shows the horizontal and vertical displacement responses obtained from LVDTs D1-D2 and D5-D8 for the peak acceleration level of 0.2g. The maximum horizontal displacement was obtained by 8.0 mm for the one horizontal excitation and 8.1 mm for the three-directional excitations; the maximum vertical displacement was obtained by 3.2 mm for the one horizontal excitation and 5.5 mm for the three -directional excitations. There is little difference between the horizontal displacement responses for the one horizontal excitation and those for the three-directional excitations, while there is a considerable amplification for the vertical displacement responses in the case of the three-directional excitations.

The seismic performance 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 shown in Fig. 16. It is obvious that the spring-damper system is an effective isolation device for the EDG. The average response ratios for the one horizontal excitation and the horizontal and vertical directions for the 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 up to 70% in the horizontal direction and 45% in the vertical direction.



(a) Artificial time-history



(b) Response spectrum

Fig. 11. Input Motion for the Shaking Table Tests

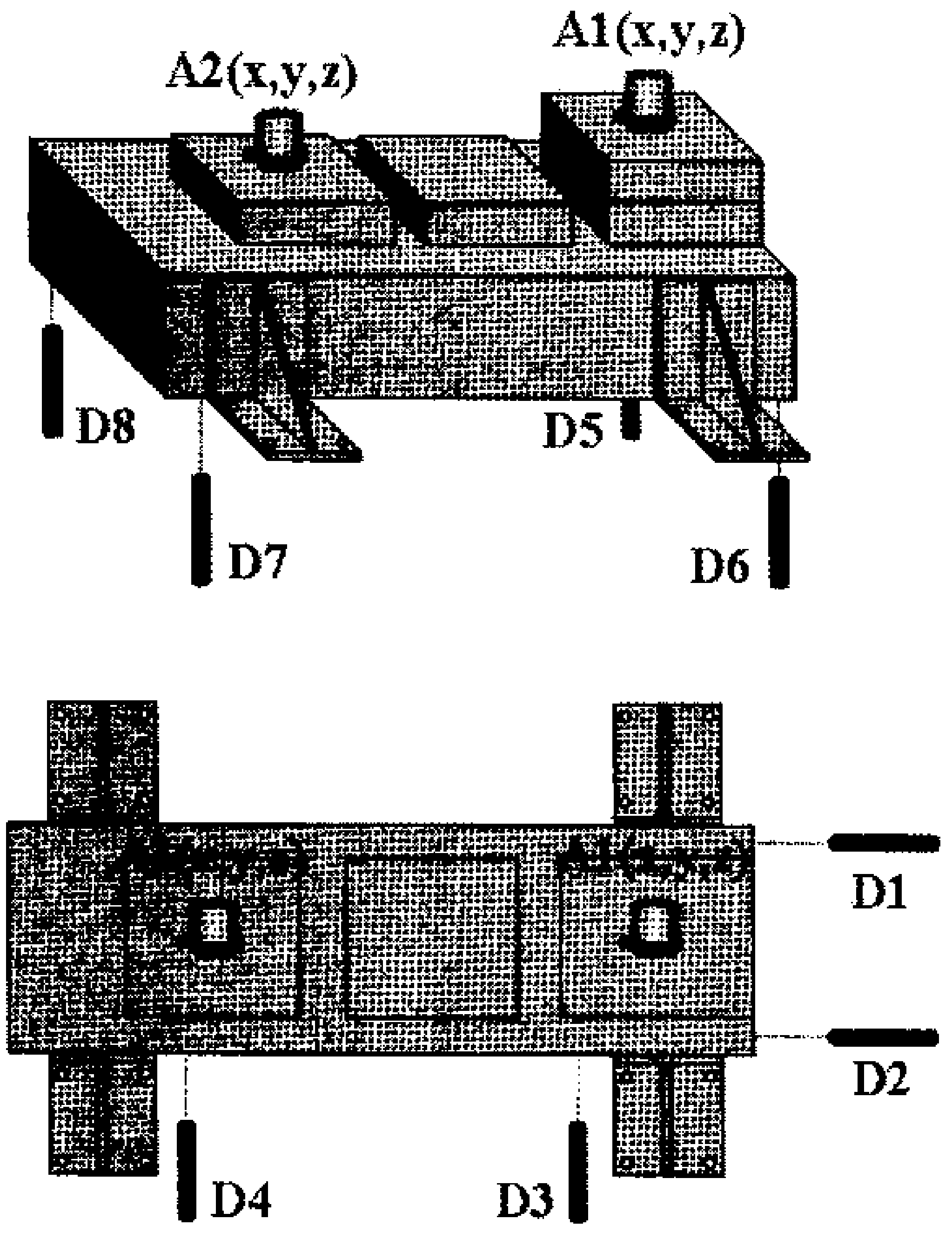
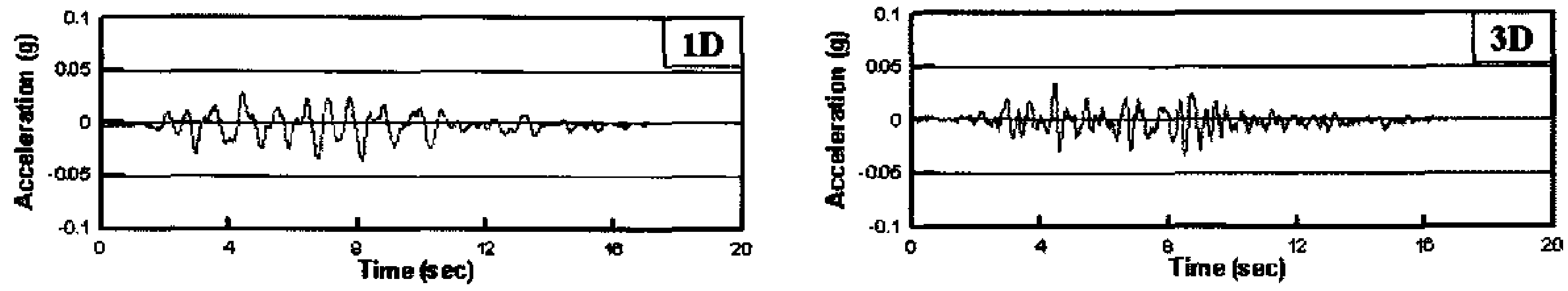


Fig. 12. Accelerometers and LVDTs Arrangement

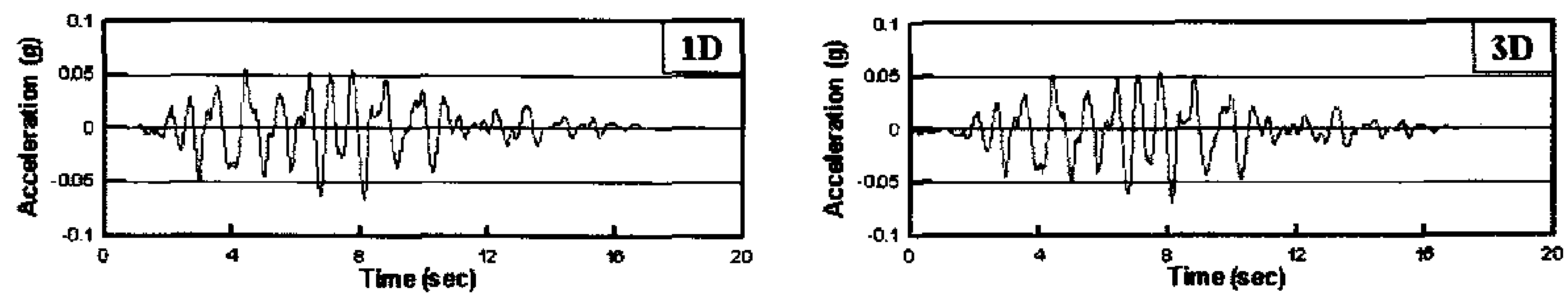
5. FRAGILITY CURVES

The governing failure mode of a base-isolated EDG must be the failure of an isolation system rather than a concrete coning or EDG failure, which is known as a dominant failure mode of an anchored EDG. Thus, the fragility curves for a base-isolated EDG should be different from those for an anchored type.

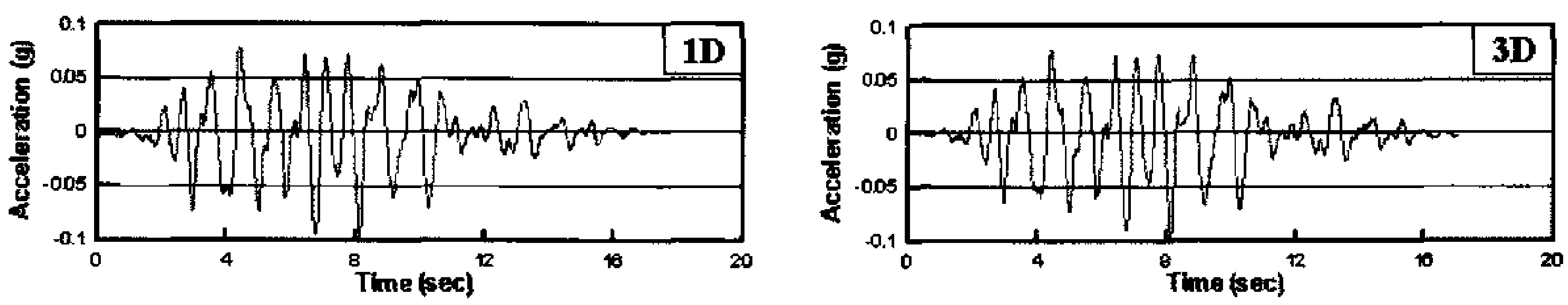
This study carried out a fragility analysis for a base-isolated and anchored EDG set. Since the natural frequency of an EDG set is generally higher than 20Hz, its dynamic behavior is similar to a rigid body motion. Thus, for simplicity of the calculation, a simple numerical model of a single degree of freedom system



(a) Peak acceleration of 0.1g

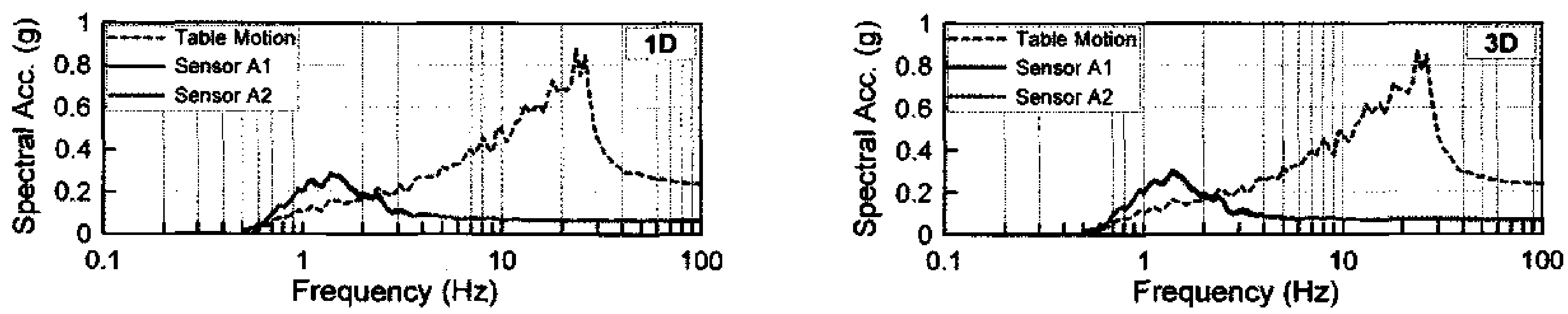


(b) Peak acceleration of 0.2g



(c) Peak acceleration of 0.3g

Fig. 13. Horizontal Acceleration Responses for Different Peak Accelerations at Accelerometer A1



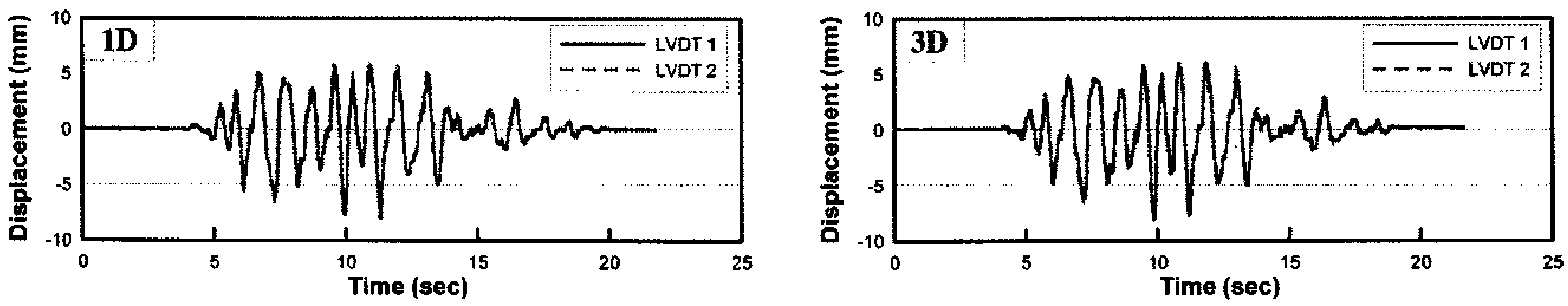
(a) One horizontal excitation

(b) Three-directional excitations

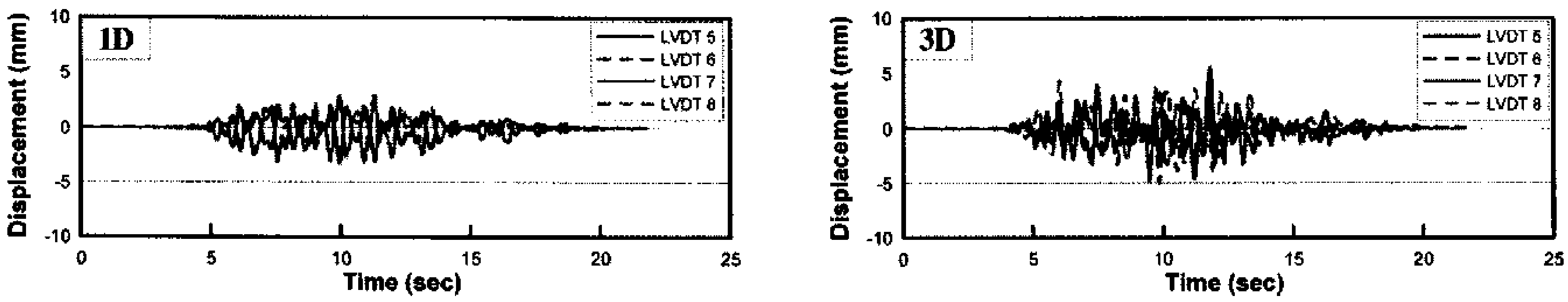
Fig. 14. Spectral Accelerations for the Peak Acceleration of 0.2g

was used for the fragility analysis. The weight of the EDG was modeled as a lumped mass at the mid-height, and spring elements which consisted of two springs for the horizontal direction and one spring for the vertical direction were introduced at the base of the EDG to represent the behavior of the base isolation system. For a fragility analysis, 38 input motions – 26 real earthquake ground motions and 12 artificial time history data of greater than magnitude 6 – were used, and the EDG failure criterion was assumed to be a maximum acceleration response of 1.2g on the EDG body.

Fig. 17 shows the fragility curves of the base-isolated



(a) Horizontal displacement (longitudinal)



(b) Vertical displacement

Fig. 15. Displacement Responses for the Peak Acceleration of 0.2g

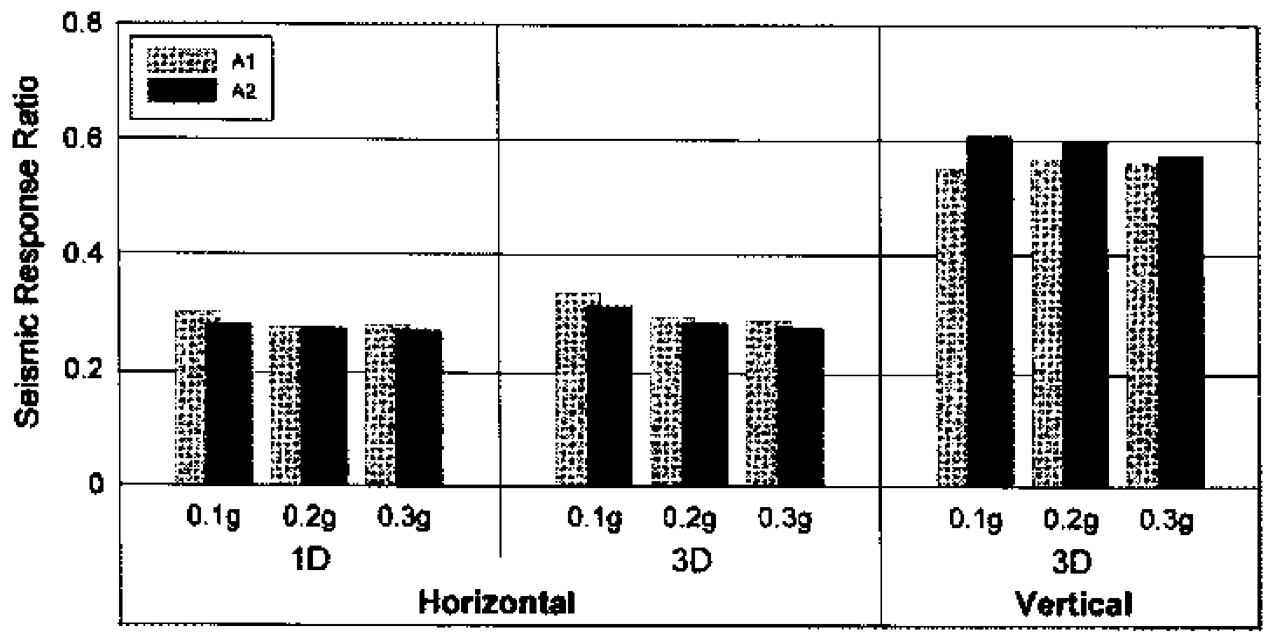


Fig. 16. Comparisons of the Acceleration Response Ratios for the Isolated EDG Test Model

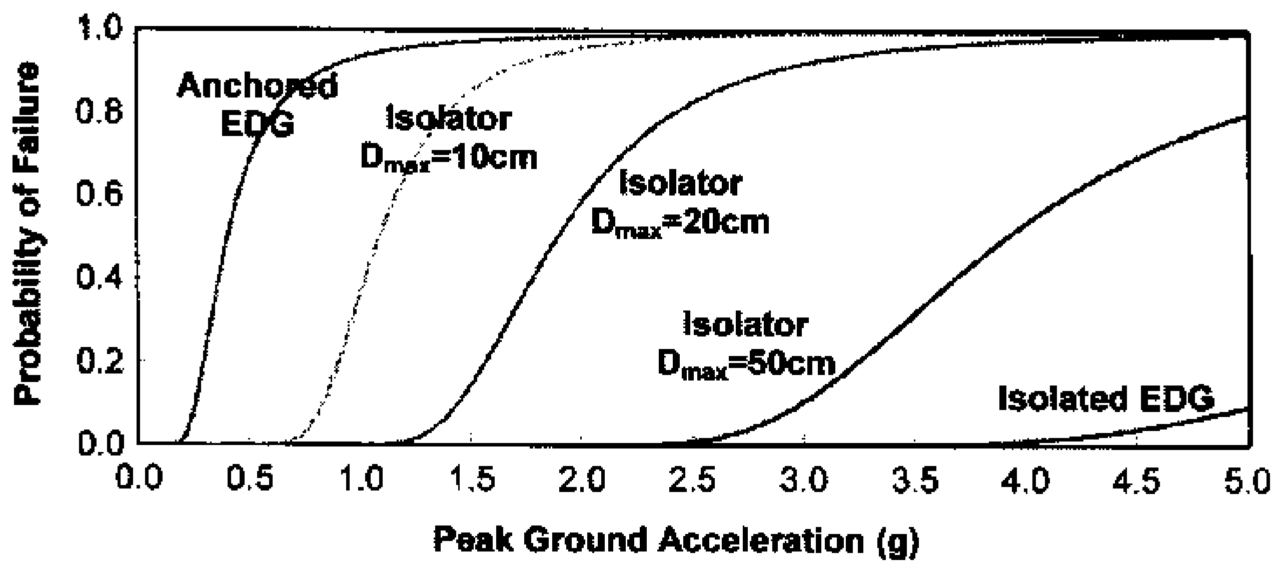


Fig. 17. Fragility Curves of the Isolated EDG Set for the Displacement Failure Criteria

EDG set for the various failure criteria of the displacement of an isolator. It is easily seen that when an EDG is supported by a base isolation system, the failure probability of the EDG body will be significantly decreased because of the large displacement of an isolator. The HCLPF (High Confidence of Low Probability of Failure) value is very sensitive to the displacement failure criteria of an isolator, and the HCLPF value is significantly increased with an increase in the allowable displacement of an isolator. For instance, when the maximum displacement of the isolator is limited to 10 cm, the HCLPF value increases by 3.6 times that of an anchored EDG, and when the maximum displacement of the isolator is limited to 20 cm, the HCLPF value increases by 6.2 times that of an anchored EDG.

6. CORE DAMAGE FREQUENCY

The contribution of a seismic-induced failure of a component or equipment to a plant's core damage frequency was evaluated for most nuclear power plants in Republic of Korea. Fig. 18 shows the contribution ratios of the safety-related components and equipment to the seismic-induced CDF (Core Damage Frequency) for Yonggwang Nuclear Units 5&6, Ulchin Nuclear Units 3&4, and Ulchin Nuclear Units 5&6. In Fig. 18, an Emergency Diesel Generator, an Offsite Power System, a Condensate Storage Tank, a Battery Rack, and a Battery Charger are found to provide a high contribution to the seismic-

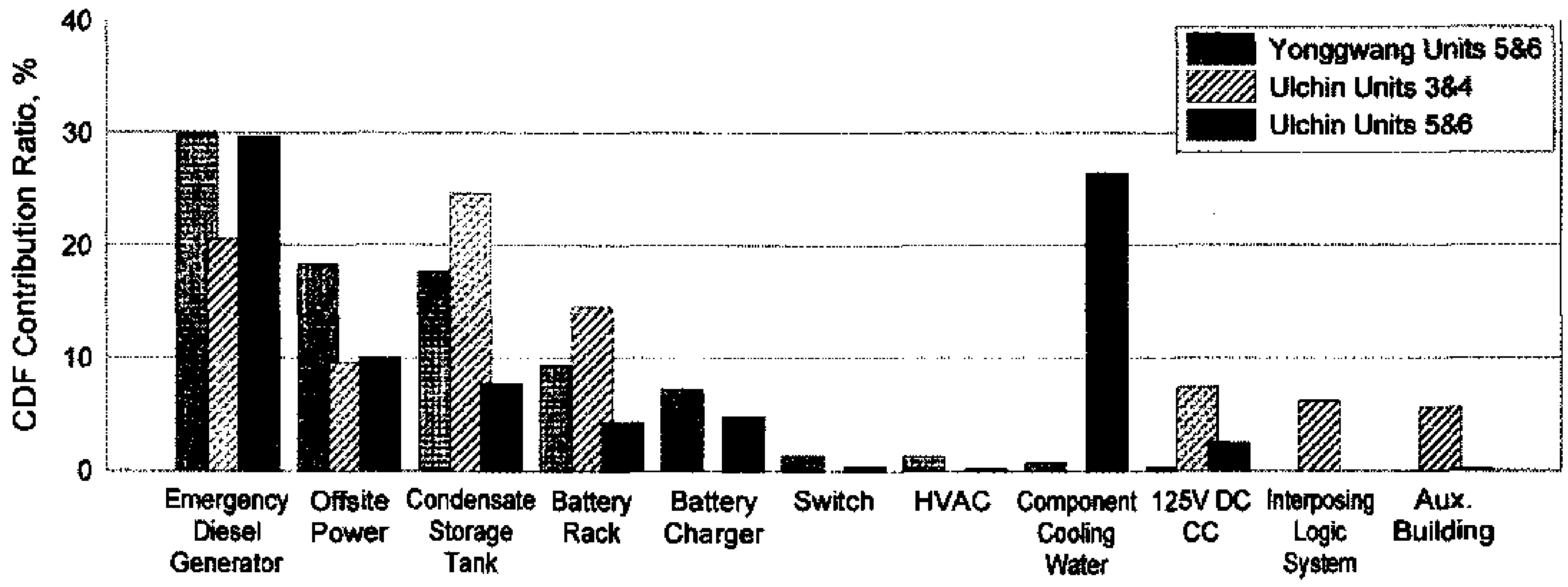


Fig. 18. CDF Contribution Ratios of the Major Equipment and Components at Korean NPPs

Table 3. Failure Mode and HCLPF Value

Nuclear Unit	Equipment/Components	Failure Mode	HCLPF (g)
Yonggwang Unit 5&6	Diesel Generator	Concrete Coning	0.38
	Offsite Power	Functional Failure	0.15
	Condensate Storage Tank	Structural Failure	0.41
	Battery Rack	Structural Failure	0.72
	Battery Charger	Functional Failure	0.41
		Structural Failure	0.52
Ulchin Unit 3&4	Diesel Generator	Concrete Coning	0.38
	Offsite Power	Functional Failure	0.15
	Condensate Storage Tank	Structural Failure	0.41
	Battery Rack	Structural Failure	0.42
Ulchin Unit 5&6	Diesel Generator	Concrete Coning	0.38
	Offsite Power	Functional Failure	0.15
	Condensate Storage Tank	Structural Failure	0.46
	ESW Pump	Anchorage	0.47
	CCW Surge Tank	Concrete Coning	0.47

induced CDF in the nuclear power plants. Above all, the contribution ratio of the EDG is so high that an increase in the seismic capacity of an EDG is essential to reduce the total plant CDF.

Table 3 shows a failure mode and a HCLPF value of the important equipment or components for each nuclear unit [25,26,27]. The HCLPF value of the EDG is considerably lower than that of the Condensate Storage Tank. Therefore, if one equipment item or component has to be selected to improve the seismic safety of a nuclear power plant, the first choice should be the EDG. The usual failure mode of an EDG is known as a concrete coning failure due to a pulling out of the anchor bolts as shown in Table 3. Thus, to increase the seismic capacity of an EDG, a base isolation system can be introduced instead of an anchor bolt system.

Core damage frequencies were evaluated through a case study for Yonggwang Units 5&6 when a base isolation system is introduced to an EDG set only. In general, a seismic-induced CDF is reduced with an increase in the seismic capacity of an EDG. However, there is a limitation to the reduction of a seismic-induced CDF. For an HCLPF value too large to be effective, even though the seismic capacity increases, the seismic-induced CDF does not decrease anymore [11]. For the EDG, it is found from Fig. 19 that there is little decrease in the seismic-induced CDF for a HCLPF value greater than 0.84g.

A seismic-induced CDF and a total CDF for Yonggwang Units 5&6 were originally calculated as 6.96E-06 and

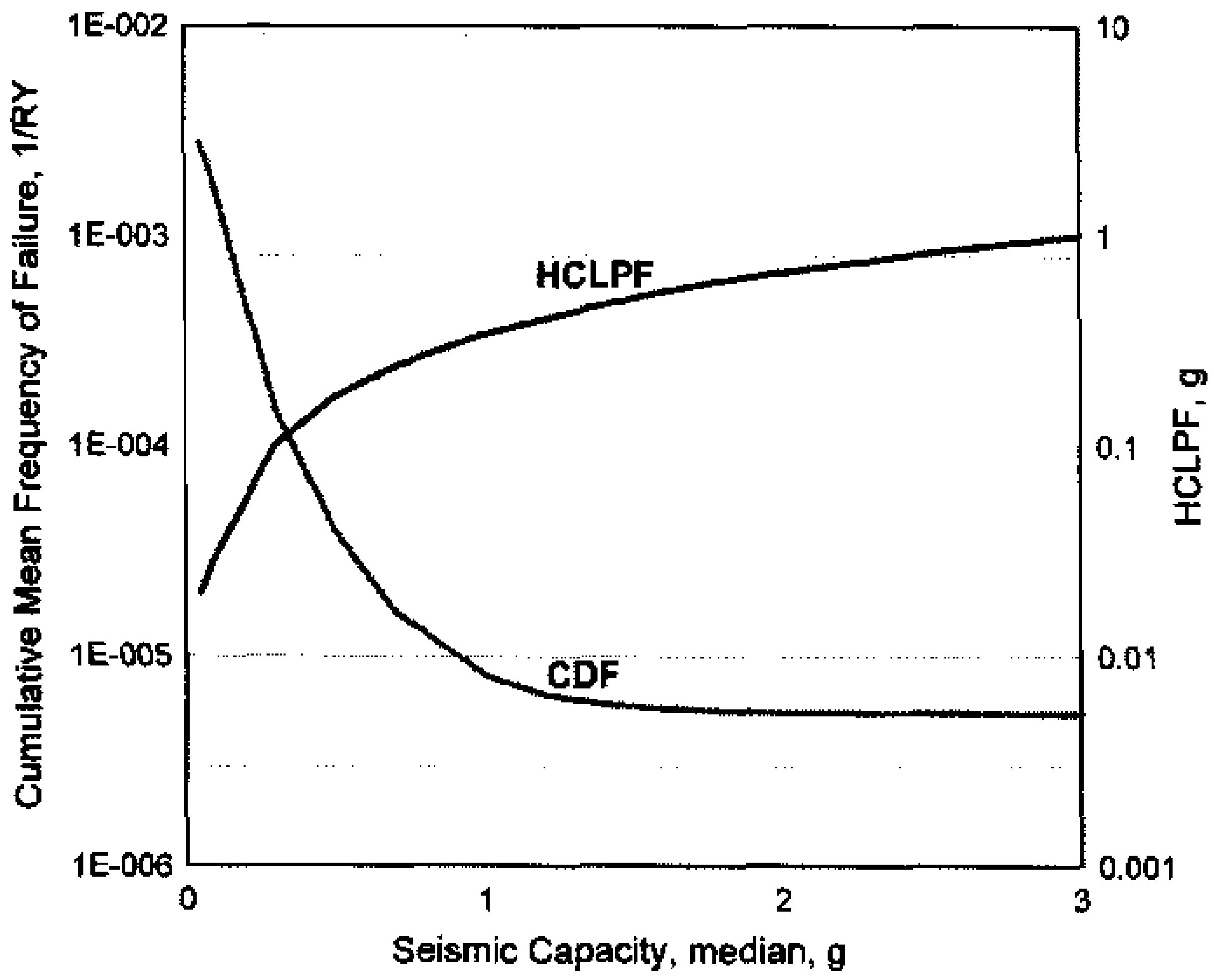


Fig. 19. Relations Between the HCLPF of an EDG and the CDF

Table 4. Comparison of the CDF Between the Anchored and Isolated Cases

Event	Anchored Case	Isolated Case
Internal	7.43E-06	7.43E-06
Seismic	6.96E-06	5.36E-06
Fire	2.35E-06	2.35E-06
Total	1.67E-05	1.51E-05

1.67E-05, respectively [25,28]. When the HCLPF value of the EDG reached 0.84g by introducing a base isolation system, the seismic-induced CDF and the total CDF were calculated as 5.36E-06 and 1.51E-05, as shown in Table 4, respectively. This indicates that a reduction of approximately 23% for a seismic-induced CDF can be achieved by a base isolation system, and finally a total CDF can be reduced by approximately 10%.

7. CONCLUSION

The performance of a coil spring-viscous damper system as a vibration and seismic isolation system for an EDG was evaluated, and then the effects of a base isolation on the fragility curves for an EDG and a CDF of Yonggwang Units 5&6 were investigated in this study. The results of this study are summarized as follows:

- The acceleration responses for the anchor bolt system and the spring-damper system during non-operating and normal operating conditions of the EDG engine revealed that the spring-damper system reduces the acceleration amplitude transmitted to the building floor slab from the EDG engine unit by more than 80%.
- The seismic responses of the base-isolated EDG model obtained by the shaking table test revealed that the spring-viscous damper system could reduce the seismic force transmitted to the EDG by up to 70%.
- The seismic fragility curves for a base-isolated EDG are different from those for a conventional type. The failure probability of the EDG body is significantly decreased because of a large displacement of an isolator, and the HCLPF value is increased with an increase in the allowable displacement of an isolation system.
- For Yonggwang Units 5&6, when introducing a base isolation system to an EDG set, a reduction of approximately 23% for a seismic-induced CDF can be achieved, and finally the total CDF can be reduced by approximately 10%.

This study has clearly shown that a coil spring-viscous damper system is an effective vibration and seismic isolation system for an EDG in nuclear power plants, and an introduction of a base isolation system to an EDG set will reduce its failure probability and increase its HCLPF value, as a result, reducing its CDF. A base isolation is a very powerful concept to improve the seismic safety of nuclear power plants through application to their safety-related structures and components. Seismic-induced CDF and total CDF could be significantly reduced by introducing a base isolation system to the safety-related facilities that greatly contribute to a seismic-induced CDF.

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