취약도변수의 개선을 위한 전기 캐비넷의 동특성 및 비선형성 평가

Modal Identification and Nonlinearity Assessment of Electric Cabinet for Improvement of Basic Fragility Variables

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국문요약

합리적인 기기의 확률론적 지진위험도 평가를 위해서는 모델의 동특성에 대한 보다 현실적인 정보가 제공되어야 한다. 이 연구에서는 심한 비선형 동적 거동을 보일 것으로 예상되는 철제 전기 캐비넷의 동특성 시험 결과 및 분석 절차를 제시하였다. 특히, 이 연구에서는 가진 강도의 크기에 따른 동특성의 비선형 변화를 집중 분석하고, 그 비선형성의 원인을 고찰하였다. 시험 결과 및 이 논문에 제시된 분석 절차를 이용하여 시험체의 동특성이 효과적으로 도출될 수 있으며, 대상 시험체는 가진 강도에 따라 심한 비선형 거동을 함을 입증하였다. 비선형성의 원인은 일반적인 재료 비선형이라기 보다는 각 부품들의 마찰력과 기하학적인 비선형성에 기인함을 발견하였다. 또한, 캐비넷 형식의 기기에 대한 합리적인 내진안전성 평가를 위해서는 각 방향별로 서로 다른 감쇠값을 적용할 것을 추천하였다.

주요어 : 확률론적 내진안전성 평가, 내진검증, 동특성분석시험, 전기 캐비넷, 비선형 거동

ABSTRACT

In order to get rational seismic probabilistic risk assessment(SPRA) of equipment, more realistic information on the dynamic properties or related facilities(structures, equipments, etc.) is required. This paper presents the procedures and the results of modal identification testing of an electric steel cabinet which is expected to have a highly nonlinear dynamic behavior due to its peculiar structural characteristics. This study is specifically focused on nonlinear variation of the modal properties in accordance with the level of exciting forces and discussing on the sources of the nonlinearity. From the test result and its interpretation, modal properties of the specimen were satisfactorily identified. The results of the study showed that the specimen behaves in considerably nonlinear manner in accordance with the excitation level. The sources of the nonlinear behavior have been revealed to be friction forces and geometrical nonlinearity rather than material nonlinearity. In addition, it is suggested to use different damping values in two horizontal directions for cabinet typed equipments to obtain more reasonable SPRA results.

***Key words** : SPRA, seismic qualification, modal test, electric cabinet, nonlinear behavior*

1. Introduction

Since NUREG-1407(1) was published, either seismic probabilistic risk assessment(SPRA) or seismic margin assessment(SMA) has been accepted as an feasible methodology for performing an individual plant examination for seismic events. In the course of SPRA, seismic fragility analysis(SFA) is the most significant and essential phase especially for structural or mechanical engineers. Both SFA and SMA have many common parts. Rational results of SFA or SMA are expected only when the basic informations on the fragility variables of related facilities

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본 논문에 대한 토의를 2001년 2월 28일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

are reasonably provided. This paper evaluated the dynamic properties of an electrical equipment to provide a feasible information for SPRA or SMA.

Safety-related equipment used in nuclear power plants shall be seismically qualified to demonstrate its ability to function as required during and/or after the time it is subjected to the forces resulting from an earthquake.(2) The seismic qualification is typically achieved through testing or analysis, though qualification by experience data is also recently acceptable.(3) Specifically, for comparatively complex equipment with small devices which are not easy to be mathematically modeled the testing method is usually selected for the qualification. In the course of a seismic qualification test program, an identification test for dynamic characteristics of the equipment, usually called an exploratory test, is performed prior to a main seismic proof test to get useful information for the best method and interpretation of results of the qualification test. A modal identification test is also frequently used for the verification of analytical models used in seismic qualification by analysis.

This paper presents the procedure and the results of modal identification tests of an electric steel cabinet for a nuclear power plant. For this study, a number of modal tests have been performed with varying levels of excitation using a large-scale 6-degrees-of-freedom shaking table. The test results were recorded and numerous sets of modal parameters, i.e., modal frequencies, damping factors, and mode shapes, were extracted through a polynomial curvefitting of the test recordings which were evaluated and compared with each other.

2. Test setup

2.1 Test equipment and shaking table

The test specimen is a seismic monitoring system central processing unit cabinet for a nuclear power plant. Its main function is alarming and monitoring seismic signals at the site of the plant. The specimen is a typical electrical cabinet of thin steel plate 650mm in width, 800mm deep, and 1550mm tall with front and rear entrance doors. Total weight of the cabinet is 317kg. The front view of the test cabinet is shown in Fig. 1(a).(4) The righthand side cabinet of the two is the junction rack cabinet discussed in this study.

As shown in Fig. 1(b), the cabinet includes very complex electric and electronic processing units and components inside. Its functional operability rather than structural integrity has more significance for seismic qualification. The cabinet consists of an internal steel frame of channels and angles, 3.2mm thick steel plate covers enwrapping the frame, with four intermediate diaphragms of thin steel plate inside. The cabinet has front and rear entrance doors and all structural components are interconnected with each other by bolting or spot

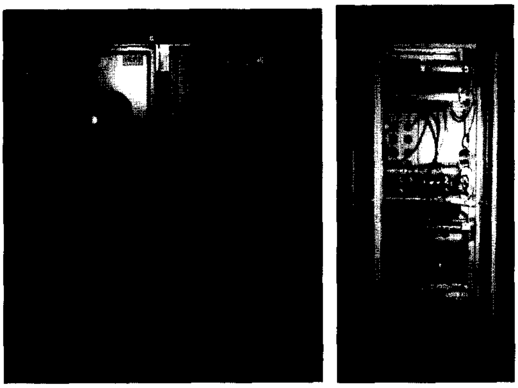

(a) Front view (b) Inside view

Fig. 1 Test cabinets on the shaking table welding. The cabinet is expected to behave in a complexly nonlinear manner with high damping characteristics under strong motion earthquake excitation. High damping values expected in the cabinet may be caused by structural sources, such as strong friction and loose connections between the components, rather than material nonlinearity.

The specimen is bolted onto the prefabricated mounting fixtures which are connected with bolts to the shaking table. The shaking table has the capacity of maximum loading of 30 ton, and table size of 4.0m×4.0m. Maximum horizontal acceleration and displacement of the table are ±1.5g and ±100mm, respectively with a frequency range of 1~50Hz.$^{(5)}$

2.2 Instrumentation and tests

The modal test for this study was performed as a preliminary phase of the main seismic proof test to extract and evaluate the modal properties of the cabinet. For easier comparison and interpretation of directional effects and coupling, one directional test in one horizontal axis was conducted independently and repeated in the other two orthogonal directions with the same pattern of excitation.

Broad band random motions with the frequency range of 1~40Hz and about eighty seconds duration were applied as the test motions and the magnitude (mean plus one standard deviation) of the motions was increased from the beginning value of 0.2g up to the maximum 1.2g at 0.2g intervals. Fig. 2 shows a typical spectral density function of the recorded actual test motion, which is reasonably flat in spite of shake-structure interaction.

For the measurement and aquisition of the test motion and response signals, a number of instrument gauges were installed on the test specimen. The instrumentation system consisted of 16 signal sensors of three different kinds as shown in Fig. 3. One accelerometer was attached to the bottom face of the shaking table for measuring and identifying the input test motion, which was also used as the base motion when

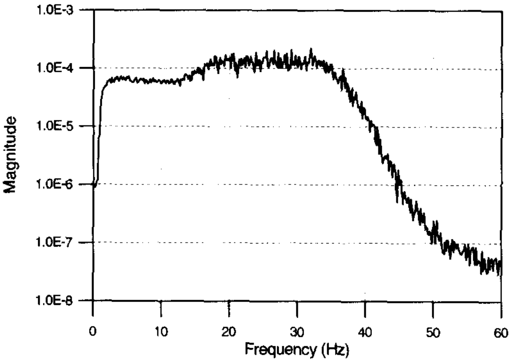


Fig. 2 Spectral density function of input motion

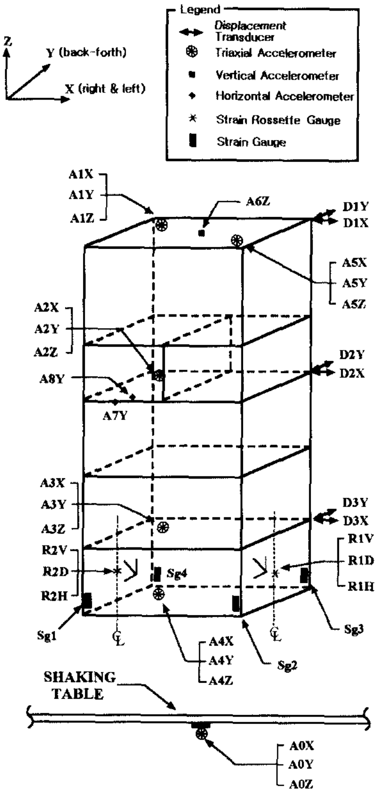


Fig. 3 Instrumentation setup of the test

computing transfer functions of the specimen. All the other instruments(six accelerometers, three displacement transducers and four strain gauges) are for measuring responses at representative locations of the specimen.

3. Evaluation of the test data

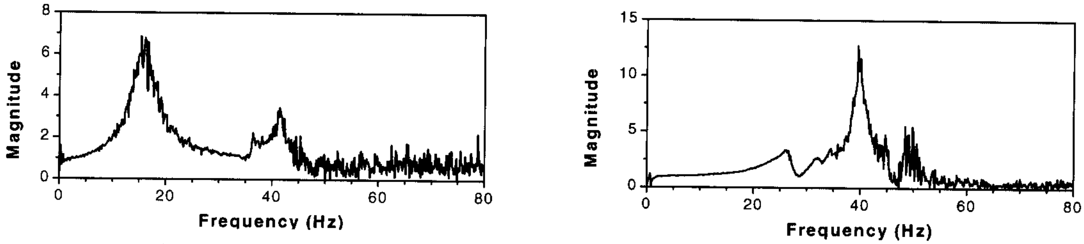
More than seven hundred data measurements (since there were 40 instrument channels and 18 tests) of the tests were recorded as time-history type in the recording system of the shaking table facility. For the experimental modal analysis of the test response data it was first necessary to convert the time-history data to the form of a transfer function. Fig. 4 shows typical transfer functions obtained for the two different levels of excitations, 0.2g and 1.0g, which represent linear and nonlinear behavior respectively. The transfer functions are at the top of the cabinet (A1 accelerometer) with respect to the base excitation (A0 accelerometer). Based on these transfer functions, modal parameters, i.e., frequencies, damping factors, and mode shapes, were estimated through the polynomial curve-fitting algorithm using the software STAR system.(6)

3.1 Modal parameter extraction procedure

The transfer function can be written in terms of modal parameters as Eq. (1) below.

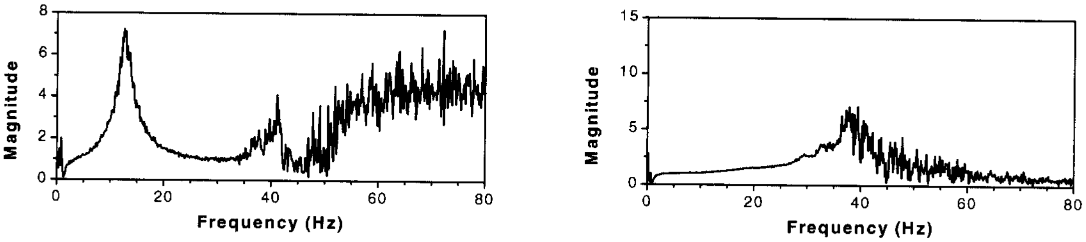
$$H_k(s)=\frac{r_k}{2i(s-p_k)}+\frac{r_k^*}{2i(s-p_k^*)} \qquad (1)$$

where, $H_k(s)$ is a transfer function computed by k-th mode, and $s(=\sigma_k+i\omega)$ is a Laplace variable, and $p_k(=\sigma_k+i\omega_k)$, σ_k, ω_k, and r_k are complex pole, modal damping, modal frequency, and residue of the k-th modal properties, respectively. * stands for conjugate pair. In the actual modal test, only the values on the imaginary axis in the form of a frequency response function, rather than the total transfer function, were obtained. Thus Eq. (1) can be reduced to Eq. (2) by selecting the imaginary axis (or frequency axis) function only.



(a) X-direction(0.2g)

(b) Y-direction(0.2g)



(c) X-direction(1.0g)

(d) Y-direction(1.0g)

Fig. 4 Typical transfer functions (A1/A0)

$$H_k(i\omega)=\frac{r_k}{2i(i\omega-p_k)}+\frac{r_k^{\ *}}{2i(i\omega-\ p_k^{\ *})} \qquad (2)$$

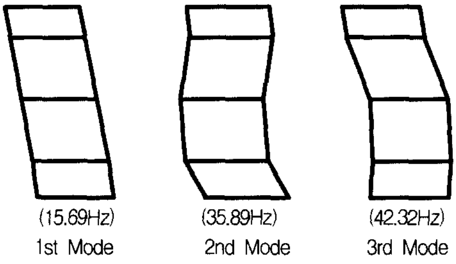
The first and second terms of the righthand side of Eq. (2) represent positive and negative functions, respectively and are symmetric. The polynomial curve-fitting algorithm adopts a least squares curve-fitting technique to the measurement data based on Eq. (3) below, which is a rearranged form of the positive term of Eq. (2).

$$H_k(i\omega)=\frac{(r_{2k}\sigma_k+r_{1k}\omega_k+i\,r_{2k}\omega)}{(\sigma_k^2+\omega_k^2-\omega^2+2\,i\sigma_k\omega)} + A0+A1(i\omega)+A2(-\omega^2) \qquad (3)$$

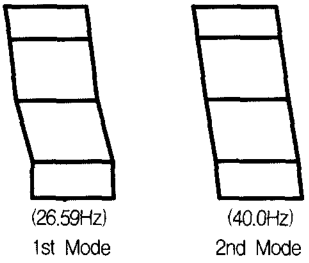
Where, ω_k, σ_k, $r_k(=r_{1k}+i\,r_{2k})$ are the k-th modal frequency, damping and residue, respectively, obtained as a result of the curve-fitting and $A0$, $A1$, $A2$ are residual function coefficients which are also identified during the curve-fitting process.

3.2 Results of evaluation

A number of modal data sets have been extracted using the various measured data obtained from different sensors. Typical values of the extracted modal frequencies and damping factors are summarized in Table 1 for the excitation levels of 0.2g and 1.0g, representing linear and nonlinear behaviors, respectively. Fig. 5 shows mode shapes corresponding to the case of 0.2g in Table 1. The values in Table 1 are from the acceleration measurements of the top floor and may give the most representative behavior. These values are averages of multiple estimations from different sensors.



(a) X-direction(right & left)



(b) Y-direction(back & forth)

Fig. 5 Schematic view of mode shapes of the cabinet

Reviewing the values in Table 1, resonance frequencies might have been reasonably extracted because they coincide well with the peak values of the transfer function in Fig. 4. However, the values of estimated damping factors show an unusual trend, i.e., damping for the fundamental mode seems to be higher than expected while the values for higher modes show much smaller values. The higher damping value for the fundamental mode is judged to be caused by incomplete connections of loose boltings and spot weldings between the components. The smaller damping

Table 1 Typical natural frequencies and damping factors extracted from the test data

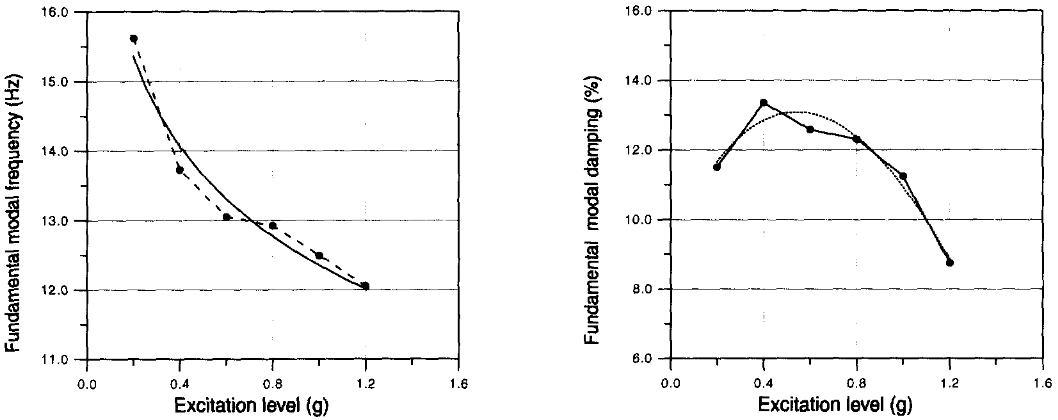
Direction	X-direction			Y-direction		Remark
Mode No.	1	2	3	1	2	- 0.2g of Excitation - A1 of Response
Frequency(Hz)	15.69	35.89	42.32	26.59	40.0	
Damping(%)	11.79	1.71	1.34	5.48	2.94	

values of the higher modes may be due to the smaller modal masses which means, in consequence, smaller friction forces between the components.

The most significant point to be noted in Table 1 is that comparison of the fundamental modal frequencies between 0.2g and 1.0g values reveals that the specimen has a highly nonlinear dynamic property. Fig. 6 shows the more specific variation of fundamental frequencies and damping factors in the X-direction in accordance with excitation levels. As can be seen in Fig. 6(a), the frequency of 15.6Hz under the lowest excitation, where the specimen behaves elastically, was gradually reduced as the excitation level increased and finally decreased to 12.0Hz at 1.2g excitation. The reduction was almost 25% which implies that the specimen has significant nonlinear characteristics and furthermore corresponds to almost 50% reduction in global stiffness of the specimen. The nonlinearity might have resulted from structural or geometrical properties rather than material nonlinearity because no permanent material deformation was found during and after the excitation tests.

The reduction of the X-directional stiffness can be observed in another relationship in Fig. 7 and 8. Fig. 7 shows the relation of peak acceleration at the top floor and strain measurements at the bottom of the side wall with respect to excitation levels. In Fig. 8, variation of estimated relative dynamic stiffness of the specimen are plotted with respect to excitation level. We can see that the reduction of stiffness ratio in Fig. 8(b) (stiffness between the top and the lower diaphragm) is much larger than the reduction in Fig. 8(a) (stiffness by relative displacement between the top and the upper diaphragm), which means that reduction of the stiffness of the whole structure can be estimated to be around 50%.

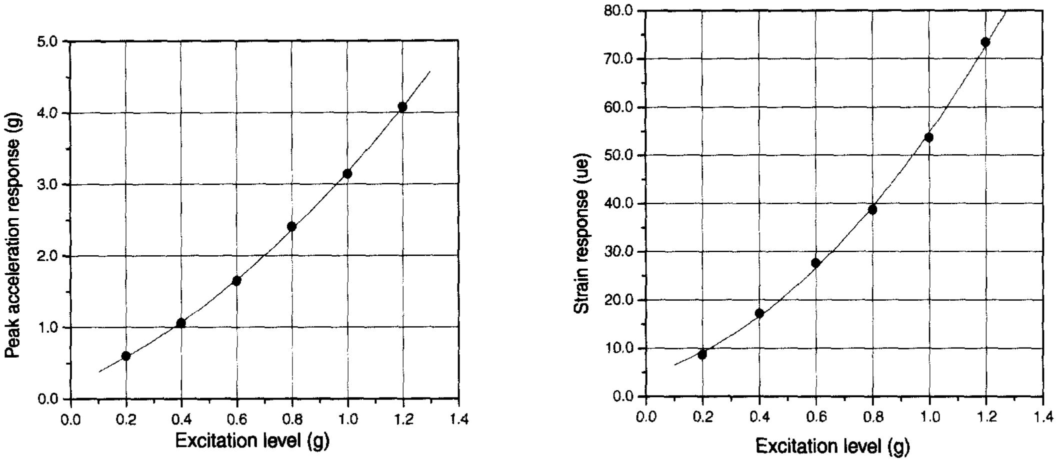
Referring to the variation of modal damping with the excitation level shown in Fig. 6(b), we can note an unusual type of variation in damping. The modal damping value increases up to some specific point of excitation level and decreases again thereafter. This trend is quite different from the generally-known phenomenon of material damping which increases monotonically as the excitation level increases. The trend of variation of damping can be



(a) Frequency

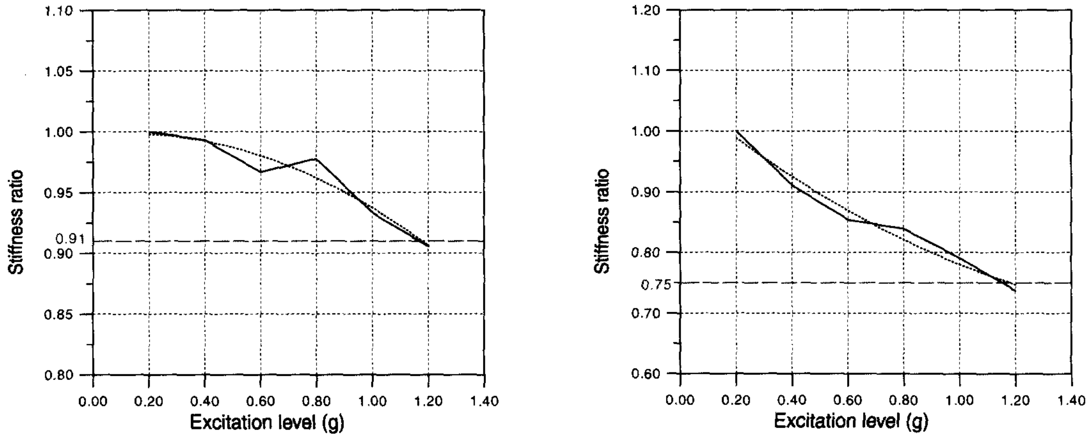
(b) Modal damping

Fig. 6 Variation of fundamental modal properties w.r.t. excitation levels (X-direction)



(a) Peak acceleration (b) Peak strain

Fig. 7 Variation of peak responses w.r.t. excitation level (X-direction)



(a) Stiffness by relative displacement between D1X and D2X

(b) Stiffness by relative displacement between D1X and D3X

Fig. 8 Reduction of stiffness ratio w.r.t. excitation level (X-direction)

explained that the damping property of the specimen is controlled primarily by friction-type and geometrical nonlinear damping rather than by material damping. Specifically, damping factors of fundamental modes were measured as 8.75% and 11.25% in the X-direction(side direction) at the excitation levels of 1.0g and 1.2g, respectively, which are the expected excitation level at the central control room floor of a nuclear power plant in Korea. These values are quite different from the recommended value of 5% as a median in practical guidance for fragility analysis provided by U.S. Electric Power Research Institute.(7)

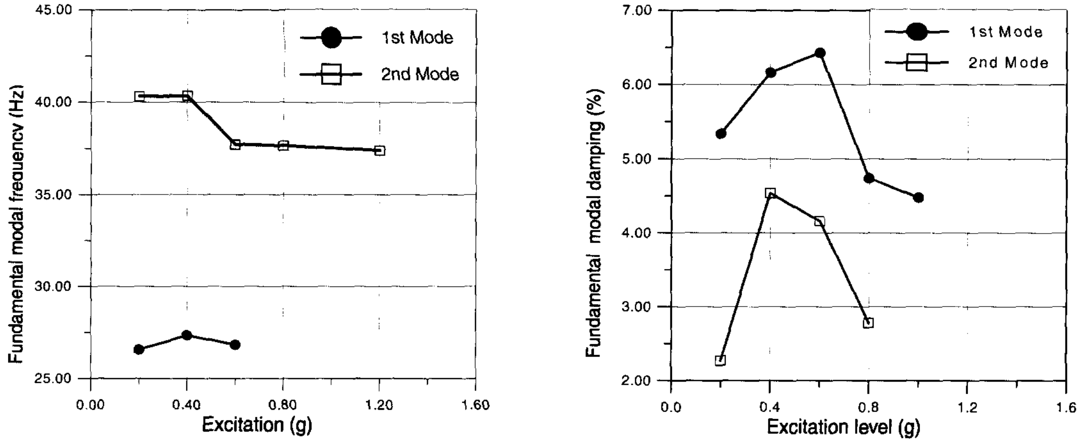
Compared with the X-directional behavior discussed up to now, the dynamic behavior in the Y-direction (back and forth direction) was found to behave in a much more complex and more severely nonlinear manner. The effects due to the dynamic behaviors of the two entrance doors intensified the complexity of the cabinet response. It is noted that the small peak near 27Hz at the low level excitation (0.2g) in Fig. 4(b) disappeared at the high level excitation (1.0g) as shown in Fig. 4(d). This phenomenon is confirmed in Fig. 9(a) which shows that the 1st mode disappeared after the 0.6g of excitation level. This means that the doors have an effect on the dynamic behavior of the cabinet at the low level excitation, while the cabinet body and the doors behave separately at the high level excitation. Thus the door's behavior does not have an effect on that of the cabinet anymore over 0.6g level excitation. Fig. 9(a) shows also that the rate of nonlinearization up to the 0.6g excitation level is more severe than after the effects of the doors disappeared.

As shown in Fig. 9(b), the general trend of the damping characteristics in the Y-direction was basically similar to that in the X-direction. However, the values of modal damping for the 2nd mode were evaluated as less than or equal to 4.5% at the high level excitation. This reduction of damping values might have been caused by the independent behavior of the doors as described above.

4. Conclusions

From the evaluation of the modal parameters of a seismic monitoring central processing unit cabinet, the specimen has been identified to behave in a considerably nonlinear manner in accordance with the excitation level. Findings and conclusions from the study results are as follows.

- The reduction of dynamic stiffness of the specimen under a possible excitation level of 1.0g, which is an expected excitation level at the cabinet location in Korea, can be more than 40% and the sources of the nonlinear behavior have been found to be due to friction forces between the loose components rather than material nonlinearity.
- Modal damping values increase up to a specific point of excitation level and decrease again thereafter. This phenomenon also results from the friction-type nonlinear behavior of the specimen.
- Modal damping factors are quite different from the recommended values for probabilistic seismic risk assessment of electrical equipments provided by the practical guidance.



(a) Frequency (b) Modal damping

Fig. 9 Variation of fundamental modal properties w.r.t. excitation levels (Y-direction)

There also exists considerable differences between the damping values for the two horizontal directions. Therefore, it is suggested that the different damping values should be used for the two horizontal directions when evaluating the seismic safety of the cabinet structure.

- The entrance doors significantly effect on the dynamic behavior of the cabinet and the extent of the nonlinearity varies in accordance with the excitation level.
- When designing and fabricating the cabinet for the safety related equipment in a nuclear power plant, careful measures are required to consider the nonlinear characteristics of dynamic properties.
- When adopting analysis techniques for seismic qualification of cabinet-typed structures, the dynamic properties of the structures including potential nonlinear behavior effects must be validated by some appropriate method.

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