In-situ testing, seismic qualification and modification analysis of nuclear plant electrical control cabinets and panels

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1. Introduction

This article describes efforts to provide a means of determining the seismically induced, in-cabinet vibration environment for safety related electric devices in the control room cabinets of an operating U.S. nuclear power plant. The in-cabinet seismic vibration environment is required to establish the seismic levels to which the device will be tested to certify seismic integrity and operability.

In this plant, electrical devices in the control room are housed in cabinets constructed of 0.18 inch thick sheet steel and steel angles and/or channel stiffeners. Cabinets are typically 90 inches high, 36 inches deep, and of varying widths. Cabinets are bolted together to form a row of cabinets; rows are typically nineteen feet in length.

In order to achieve the objective of this effort, three items are required: a dynamic model for each of the cabinet rows, a definition of the seismic excitation, and an analytical tool that can calculate the in-cabinet dynamic environment for the existing condition and can evaluate the effects of modifications to a cabinet.

A row of cabinets can be treated as a linear structural system. Thus, the information required for a dynamic model are its modal properties. These modal properties consist of the row's natural frequencies, mode shapes, and participation factors. In this effort, the frequencies and mode shapes were determined through low-level, in-situ testing of the cabinet rows. Participation factors were calculated by first estimating a row's mass distribution, refining that estimate using mass orthogonality principles, and then calculating the participation factors using the final mass distribution and the mode shapes determined through the in-situ tests. A discussion on the testing and data analysis procedures is provided in Section 2.1.

The cabinets' seismic excitation is defined by the floor response spectra (FRS) for the control room floor. For analyses in this effort, the cabinets are subjected to seismic input in all three directions.

The in-cabinet seismic enviornment for a particular device is defined by the amplified response spectra (ARS; one ARS for each of the three directions of motion) at the device's location. These ARS are developed analytically by applying the excitation defined by the FRS to the cabinet base, calculating the response at the device location, and then developing the ARS from that response. In order to perform this calculation, a more detailed definition of the floor motion than the FRS is required. One means of acquiring this more detailed definition is to develop a floor motion time history that envelops the FRS. The cabinet response is then calculated by numerical integration of that time history. Alternatively, this procedure can be performed in the frequency domain. The power spectral density function (PSD) of the floor motion that envelops the FRS is developed. The cabinet response is then calculated by multiplying the floor PSD by the cabinet's transfer function. The frequency domain approach is used in this effort. Technical details on the development of a PSD from a FRS are provided in Section 2.2.

The final item required to meet the objectives of this effort is an analytical tool that can perform the required calculations. Stevenson & Associates has developed a microcomputer-based software package , EDASP (Equipment Dynamic Analysis Software Package) [1], to meet that requirement. This package performs three basic analytical tasks. First, a PSD can be automatically developed from a FRS. Second, given a cabinet's modal properties and the floor PSD, the ARS at any point in the cabinet can be calculated. Finally, given a set of modifications to the cabinet (mass and/or stiffness), the modal properties of the modified cabinet are calculated using the original modal properties as a basis. Details on the program's use and technical basis can be found in Section 2 of this article.

2. Test and Analysis Procedures

2.1 In-Situ Modal Testing

The free vibration of a multi-degree-of-freedom (MDOF) linear structure is defined by the following set of N coupled differential equations:

$$[M]\ddot{\underline{x}} + [C]\dot{\underline{x}} + [K]\underline{x} = 0, \qquad (1)$$

where
$\underline{x}$ = displacement vector (Nx1)
$[M]$ = mass matrix (NxN)
$[C]$ = damping matrix (NxN)
$[K]$ = stiffness matrix (NxN).

Using the coordinate transformation $\underline{x} = [P]\underline{a}$, (2)

where $[P]$ = modal matrix (NxN) containing N mode shapes $\underline{p}_i$ (Nx1), stored columnwise
$\underline{a}$ = vector of modal amplitudes (Nx1),

Equation (1) can be rewritten as a set of N decoupled differential equations, the ith one of which is:

$$GM_i\ddot{a}_i + 2z_i w_i\dot{a} + w_i^2 a = 0, \qquad (3)$$

where
GM_i = generalized mass of the ith mode
z_i = damping coefficient of the ith mode
w_i = frequency (rps) of the ith mode.

The mode shapes, frequencies, and generalized masses constitute the dynamic model of the linear system. The objective of the in-situ testing is to determine the mode shapes, frequencies and generalized masses of each row of cabinets.

The first step in the test procedure is to lay out a measurement grid on the cabinet row. For the subject cabinet rows this grid consists of points roughly fifteen inches on center. The exact spacing is a function of the cabinets' width and device locations. The coordinates of the measurement grid are then recorded.

An electrodynamic shaker is then attached to one of the points in the grid, and an accelerometer is placed at a second grid point. Shaker and accelerometer locations, and instrumentation calibration factors are then recorded. The shaker is activated and the shaker force output and the accelerometer signal are fed into a multi-channel dynamic signal analyzer. The analyzer performs a Fourier analysis of the two signals, developing and recording the transfer function relating these two signals. The accelerometer is then moved to another grid point and the process is repeated. A transfer function is recorded for each point in the measurement grid.

The theoretical transfer function relating acceleration at point 1 to force at point 2 is developed by taking the Fourier transform of Equation (3) and then applying the coordinate transformation defined by Equation (2). This results in:

$$H(w) = \frac{p_{i,1}p_{i,2}}{GM_i} \cdot \frac{w^2}{w^2 - w_i^2 - 2jz_i w_i w} \qquad (5)$$

The frequencies, mode shapes, and generalized masses are then determined by fitting the theoretical transfer function equation to the test data. The final piece of information needed to complete a cabinet row's dynamic model is the mass distribution.

2.2 Seismic Base Excitation

The cabinet rows are subject to seismically induced base excitation. That base excitation is quantified by the floor response spectra (FRS) at the cabinet locations. All cabinets in this effort reside in the control room. The horizontal and vertical FRS and corresponding PSD's developed by the EDASP program for the control room are shown in Figures 1a and 1b, and 2a and 2b, respectively.

In order to calculate the ARS at a device location, the FRS must be converted to a different form. If the ARS calculation is to be performed in the time domain, that form is the floor acceleration time history. If the ARS calculation is to be performed in the frequency domain, that form is the floor acceleration power spectral density (PSD). In this effort, all analyses are performed in the frequency domain.

The PSD is derived from the FRS by inverting the following relation:

$$R^2(w) = -2m_0 \ln[-3.14\sqrt{(m_0/m_2)}\ln(1-r)/T], \qquad (6)$$

where

$$m_n = \int_0^\infty p^n S(p,w)\,dp$$

$$S(p,w) = \frac{w^4 + 4(wzp)^2}{(p^2-w^2)^2 + 4(wzp)^2} \, PSD(w)$$

$PSD(w)$ = floor acceleration power spectral density
$R(w)$ = floor acceleration response spectrum
z = damping coefficient associated with $R(w)$
r = probability of exceedance
T = duration of motion.

A complete discussion of the derivation and inversion of the above equation is available in Reference 2. Briefly, the relationship between PSD and FRS is established by assigning a probability of exceedance (r) to the FRS. This exceedance value is the probability that the value of the FRS will be exceeded during a seismic event of length T. Treating the seismic event as a Gaussian process, the relationship between the FRS (a measure of peak response), and the PSD (a statistical measure of motion), can then be derived.

2.3 Calculation of Amplified Response Spectra (ARS)

The in-cabinet seismic environment of a particular device is defined by the ARS (one ARS for each of the three directions of motion) at the device location. This calculation is performed in the frequency domain by first deriving the floor PSD from the FRS, then applying the floor PSD to the structural model (derived via the in-situ testing) to calculate the amplified PSD at the device location, and finally deriving the ARS from the amplified PSD using the same procedure described in Section 2.2 for the floor PSD/FRS calculation.

The amplified PSD is related to the floor PSD through the following equation:

$$A_i(w) = \sum_j \sum_l p_{i,j} p_{i,l} \mathrm{Re}[H_j(w) H_l^*(w)] \sum_k G_{l,k} G_{j,k} S_k(w) + \left(2 \sum_j G_{j,q} p_{k,j} \mathrm{Re}[H_j(w)] + 1\right) S_q(w), \tag{7}$$

where $A_i(w)$ = amplified PSD at the ith degree-of-freedom (DOF) - a DOF is described by a node number and a direction number
$S_i(w)$ = floor PSD in the ith direction
$p_{i,j}$ = mode shape value at the ith DOF in the jth mode
$G_{i,j}$ = participation factor in the ith direction for the jth mode
$H_i(w) = w^4/[w_i^2 - w^2 - 2jz_s w_i w]$
$H_i^*(w)$ = complex conjugate of $H_i(w)$
w_i = frequency (rps) of the ith mode
z_s = damping coefficient of the cabinet structure.
q = the direction number of the ith DOF.

The first term in the above expression is essentially the acceleration PSD (of the ith DOF) relative to ground. Note that the influence of excitations in all three directions of motion are included. The second term incorporates the base motion in the direction of the ith DOF, thus $A_i(w)$ is the absolute amplified acceleration PSD. Once the amplified PSD is calculated, the ARS is developed using the procedure outlined in Section 2.2.

2.4 Evaluation of Modifications

During the course of plant's operating life, it can be anticipated that modifications - primarily removal or installation of electrical devices -

of the as-tested electrical cabinet rows will be required. These modifications may impact the structural characteristics of the cabinet row, and thus affect the ARS developed for device qualification. It is therefore desirable to have a means of evaluating these modifications, short of retesting the modified cabinet row.

Evaluation of modifications can be performed by using the modal data of the original cabinet row as the basis for the modal data of the modified cabinet row. The equations of motion of the modified cabinet row are obtained by modifying Equation (1):

$$([M] + [dM])\ddot{\underline{x}} + ([K] + [dK])\underline{x} = 0, \qquad (8)$$

where [M] and [K] are the mass and stiffness matrices of the original cabinet row, and [dM] and [dK] describe the modifications. Applying the coordinate transformation defined in Equation (2) to Equation (8) yields:

$$([GM] + [P]^t[dM][P])\ddot{\underline{a}} + ([GK] + [P]^t[dK][P])\underline{a}, \qquad (9)$$

where [GM] and [GK] are diagonal matrices containing the generalized masses and frequencies of the original cabinet row, [P] contains the mode shapes of the original cabinet row, and $\underline{a}$ is the displacement vector of the original mode shapes.

Equation (9) can be diagonalized by performing an analytical modal extraction. This will result in a set of frequencies, generalized masses, and mode shapes for the modified system. Once this data is acquired, the ARS for the modified cabinet row can be calculated using the procedures discussed in the previous sections. The Equipment Dynamic Analysis Software Package (EDASP) contains the software necessary for the above calculations. The user provides the mass and/or stiffness modifications, the software generates the modal data for the modified system, the software can then automatically generate the ARS for the modified system.

3. Results

3.1 In-situ Modal Testing

In-situ modal test results consist of a set of frequencies and mode shapes for each of the nine cabinet rows tested. All frequencies and mode shapes up to at least 33 Hertz were developed from the test data. The modal data for a typical cabinet row consists of four to six mode shapes ranging in frequency from 15 Hertz to 35 Hertz. The first two or three mode shapes involve overall bending or twisting of the cabinet row. The higher frequency mode shapes involve a combination of overall bending and twisting with local panel deformations. Figure 3 shows a typical fundamental mode shape of a cabinet row.

3.2 Calculation of Amplified Response Spectra (ARS)

Once a cabinet row's modal data (mode shapes and frequencies) and mass distribution have been determined, and once the floor acceleration PSDs have been established, the ARS at any point in the cabinet row can be calculated. The ARS for a mid-height location on a typical cabinet row is shown in Figures 3 and 4 (point 46) for the two horizontal directions. Figure 6 shows the location of the measurement points in the cabinet row. For comparison, the horizontal FRS overlays the ARS in the Figures.

These ARS were calculated using the floor acceleration PSD corresponding to the horizontal SSE FRS as the base excitation in both the X and Z directions. No input in the vertical direction was applied; the cabinet row is rigid vertically, thus the vertical ARS at any point is simply the vertical FRS. Per the recommendation of IEEE Standard 344-1975 [3] for welded steel structures, the cabinet motion was calculated using a 4% damping coefficent. The ARS were calculated from this motion using a 1% damping coefficient. Note that the 4% damping coefficient used to calculate the cabinet motion is of physical significance, while the 1% damping coefficient used for the ARS is an arbitrary choice.

The horizontal response of the example cabinet row is dominated by its first mode, which has a frequency of 24.9 Hertz and a shape as shown in Figure 3. This is a predominantly Z direction mode, with the maximum response occuring at point 46. The effect of this mode is clear in Figure 4. The Z direction ARS is identical to the horizontal FRS out to approximately 15 Hertz. The first mode response results in the strong spike at 25 Hertz, and the zero period acceleration (ZPA) has increased from 0.45g to 0.90g. Thus the cabinet motion at point 46 in the Z direction is essentially the floor motion with a strong 25 Hertz sinusoid superimposed. That 25 Hertz sinusoid added to the floor motion results in a peak acceleration at point 46, in the Z direction, of 0.9g.

4. Conclusions

In-situ testing of electrical cabinets and the use of a software package such as EDASP offer the capability to conduct reliable response analysis and update equipment responses due to physical changes. Its advantages over analytical modelling are speed, cost and, most importantly, reliability.

5. References

1. Stevenson & Associates, Equipment Dynamic Analysis Software Package Theory and Verification Document Version 1.0, Revision 2XT, February 6, 1984.
2. Kaul, M.K., "Stochastic Characterization of Earthquakes Through Their Response Spectra", Earthquake Engineering and Structural Dynamics, Volume 6, pp. 497-509 (1978).
3. IEEE, IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations, IEEE Standard 344-1975.

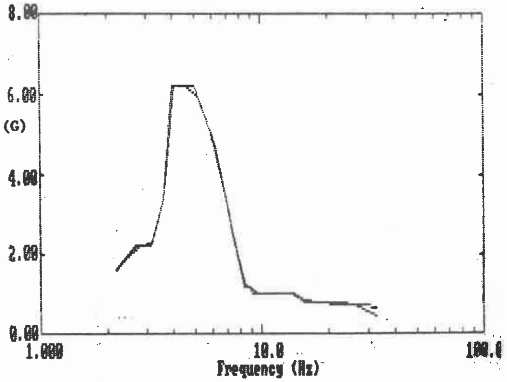


Figure 1a. Computed vs. Desired Horizontal Floor Response Spectrum (SSE, 1% Damped)

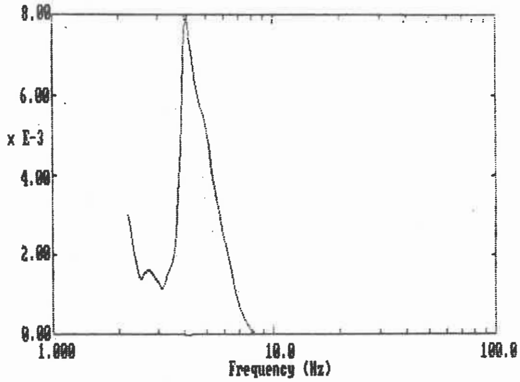


Figure 1b. Horizontal Floor Acceleration Power Spectral Density (SSE)

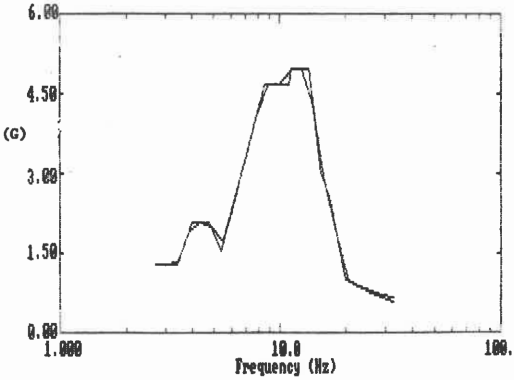


Figure 2a. Computed vs. Desired Vertical Floor Response Spectrum (SSE, 1% Damped)

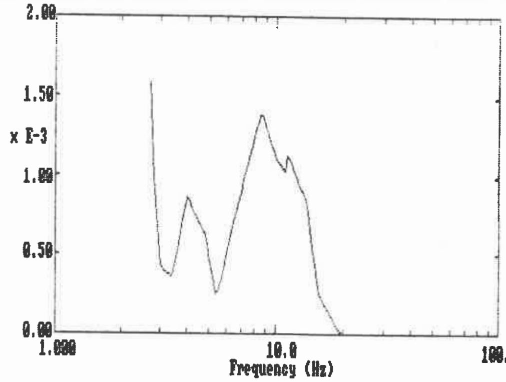


Figure 2b. Verical Floor Acceleration Power Spectral Density (SSE)

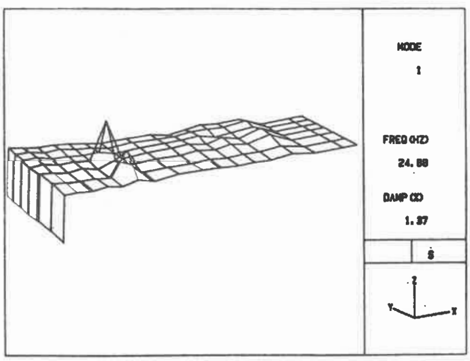


Figure 3. First Mode of Cabinet Row

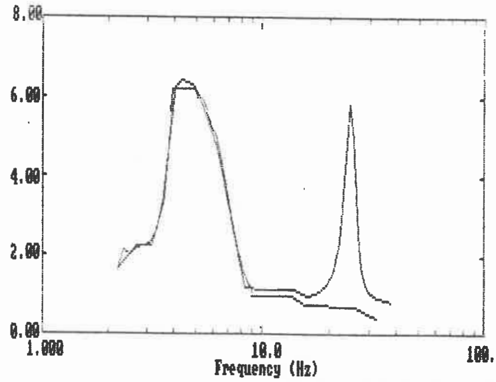


Figure 4. ARS at Point 46, Z Direction, Cabinet Row vs. Horizontal FRS (SSE, 4% Cabinet Damping, 1% ARS Damping)

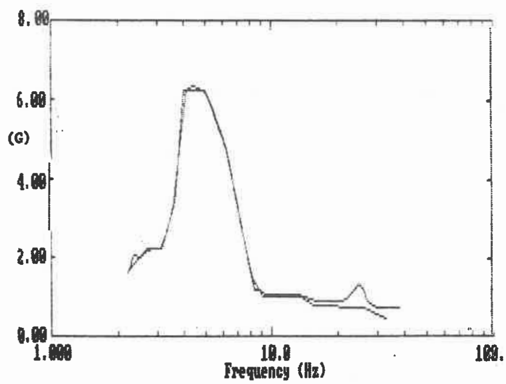
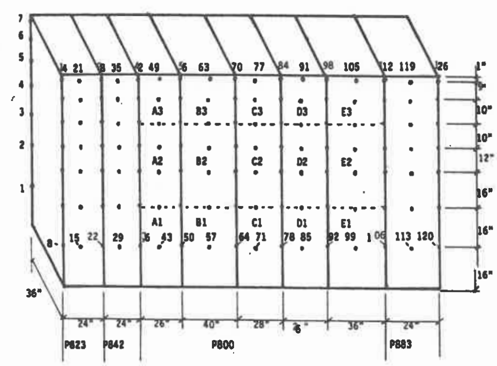


Figure 5. ARS at Point 46, X Direction, Cabinet Row vs. Horizontal FRS (SSE, 4% Cabinet Damping, 1% ARS Damping)



MEASUREMENT GRID FOR CONTROL PANELS

Figure 6.