Seismic Qualification of Nuclear Equipment under Multiple Support Excitations

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1 INTRODUCTION

Envelope Response Spectrum (ERS) method, wherein an envelope response spectrum obtained by superimposing individual support spectra is utilized in the analysis, is presently most popular analytical tool for the seismic qualification of multiply supported nuclear equipment and piping. This method generally gives conservative results and is therefore readily acceptable by ASME code (Ref.1). Low computational cost is the additional reason for its popularity. Multi Support Response Spectrum (MSRS) method (Ref.2,3,4,5), on the other hand, adequately accounts for the effect of individual support spectra and is generally found to give realistic response (Ref.6,7,8,9), as compared to over-conservative results by ERS method. This has led to a general notion that ERS response should always be higher than MSRS. However, MSRS method is preferred over ERS method only when the objective is to reduce the conservatism in design (Ref.10). The purpose of the present study is:

a) To show that ERS is not always conservative method as compared to MSRS method. This is particularly shown to be the case for the overhanging equipment, i.e., those equipments which are projecting above the upper elevation support.

b) To establish the reasons for unconservativeness of ERS method in such cases.

c) To evaluate a simplified criterion which can be utilized for selection of proper method of analysis, between ERS & MSRS methods, for the seismic qualification of nuclear equipment.

In addition, interim conclusions are also made on the support group combination rule to be used in the MSRS method.

2 METHODS OF ANALYSIS

Seismic response characteristics of equipment with and without overhang subjected to lateral excitations are investigated. Studies are carried out on coupled as well as decoupled equipment models. In case of coupled model, equipment is modelled along with the representative primary civil structure whereas in decoupled model equipment alone is analysed for non-uniform support excitations. Following methods are considered for studying equipment response by Finite Element software PHILM (Ref.11):

Method A : Time history (Fig.1) analysis of coupled equipment. The direct integration scheme with Milnor-theta operator, as well as stiffness proportional damping and time step equal to 0.1 times the minimum period of interest is used in the analysis.

Method B : Response spectrum (Fig.2) analysis of...
coupled equipment.

Method C: Decoupled ERS analysis. The support spectra derived from the acceleration time histories obtained in method A at the primary structure points of equipment support are superimposed for use in this method.

Decoupled ERS method with following support group combination rules:

Method D1: Algebraic combination.
Method D2: Square Root of Sum of Squares (SROSS) combination.
Method D3: Absolute combination.

In addition, equipment & primary structure are connected by truss elements to avoid Seismic anchor movement induced accelerations/forces in the equipment, 100% of equipment mass is excited either by considering adequate number of modes or by applying missing mass correction. Mass ratio of equipment & primary structure is kept small enough to enable de-coupling (Ref.1), unsmoothed spectra are used in coupled as well as decoupled spectral analysis and uniform damping ratio (2% critical damping) is assumed for primary structure as well as equipment. These precautions are taken to avoid any uncertainty from the point of view of comparison of above methods of analysis.

3 RESPONSE SPECTRUM METHODS

ERS and ERSB methods follow identical procedures for superposition of modal and directional responses (Ref.12) and differ only in the evaluation of peak modal response. Effect of individual support spectrum is accounted in ERSB method by modifying participation factor through influence function vector. The comparative assessment of procedures of evaluating peak modal and total response, for excitation in a given direction, in ERS and ERSB methods is as follows:

<table>
<thead>
<tr>
<th>Response Quantity</th>
<th>ERS Method</th>
<th>ERSB Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modal displ., $u$</td>
<td>$\phi = \phi_i^a S_{a_i}^n / u^2$</td>
<td>$\phi = \phi_i^k S_{a_i}^k / u^2$</td>
</tr>
<tr>
<td>Relative Accl., $v_{re}$</td>
<td>$\sqrt{\frac{i (\Gamma_i \delta_i S_{a_i}^n)^2}{\beta_i}}$</td>
<td>$\sqrt{\frac{i (\phi_i^k \delta_i S_{a_i}^k)^2}{\beta_i}}$</td>
</tr>
<tr>
<td>Rigid Accl., $v_{ri}$</td>
<td>$\sqrt{\frac{i (1 - \Gamma_i \delta_i S_{a_i}^n)^2}{\beta_i}}$</td>
<td>$\sqrt{\frac{i (1 - \phi_i^k \delta_i S_{a_i}^k)^2}{\beta_i}}$</td>
</tr>
<tr>
<td>Total Accl., $v_r$</td>
<td>$\sqrt{v_{re}^2 + v_{ri}^2}$</td>
<td>$\sqrt{v_{re}^2 + v_{ri}^2}$</td>
</tr>
</tbody>
</table>

It is evident from above that the ERSB response can be higher than ERS if:

$$k \Gamma_i \delta_i S_{a_i}^k > \phi_i^k S_{a_i}^k$$

However, presence of term $S_{a_i}^n$ on right hand side of above equation is generally the reason for relatively higher response estimate by ERS method.

6 EQUIPMENT RESPONSE
Coupled model of equipment, influence function vectors and acceleration response at equipment degrees of freedom, as calculated from various methods, for the case of equipment with and without overhang is shown in Fig.3 & 4 respectively. Equipment in both the cases are modelled by uniform beams. It is observed that ERS method is overconservative for equipment without overhang whereas it is unconservative in the overhang segment for the case of overhanging equipment. However NSHS method yields conservative response for both class of equipment.

5. REASONS FOR UNCONSERVATISM OF ERS METHOD:

5.1 Magnification of Response Due to Relative Support Motion:

ERS method assumes identical spectral acceleration over the entire structural system, signified by presence of III vector in modal participation factor, and provides no scheme for accounting magnification of response in the overhanging region of equipment resulting from the relative support motion. However, the same is possible in terms of influence function vector in case of NSHS method. This aspect is studied by analyzing a hypothetical massless equipment with a single lumped mass at the top of overhang as shown in Fig.5. The variation of spectral acceleration, as evaluated in methods C and D1, along the equipment height is also shown in Fig.5. The response quantities estimated by various methods are shown in Table 1. It can be seen that the ERS response is unconservative whereas results of NSHS method are in excellent agreement with time history results. It may be noted from Fig.5 that, for ERS method, variation of spectral acceleration is conservative for the supported masses (masses located between the supports) and unconservative for overhanging masses.

5.2 Contribution of Antisymmetric Modes:

Antisymmetric modes are not excited in ERS method since this method is essentially classical uniform support response spectrum method which, while evaluating peak modal response, assumes identical and inphase support excitations. However, in case of multi-support problems, the support excitations are non uniform and therefore antisymmetric modes must get excited even if the support excitations are perfectly in phase. Antisymmetric modes in NSHS method, unlike ERS method, does not yield zero participation factor because of presence of influence function vector in and not the III vector. Contribution of antisymmetric modes is important for overhanging equipment since, with increasing overhang, the equipment first mode itself becomes sensitive to antisymmetric vibration.

The aspect of antisymmetric mode is studied by analyzing a two mass system, Fig.6, which is derived such that the first mode itself is nearly antisymmetric. Results of analysis are shown in Table 2. It can be seen that antisymmetric mode could not be excited in ERS method leading to severe unconservatism whereas NSHS methods yield conservative response since the same could be accounted.

6 EVALUATION OF CRITERION FOR SELECTION BETWEEN ERS & NSHS METHODS OF ANALYSIS

A simple criterion for the selection of proper method of analysis, between ERS and NSHS methods, is evolved for the analysis of generalised equipment of non uniform mass and stiffness distribution. The criterion is based on the numerical assessment of equipment response in first mode only which is justified in view of dominant contribution of first mode in the total response of equipment. It has been assumed that the upper support acceleration (SI) is higher than the lower support acceleration (S2) which is practically the case for the equipment supported from the different elevations/floors of a single civil structure like reactor building. The parameteric variation in a/l ratio (ratio of length of overhang to the total equipment length), S2/S1 ratio and support group combination rules is performed to assess the equipment response characteristics by methods C,D1,D2 & D3. Effect of variation of a/l ratio on the variation of modal frequency, modal mass and ERS & NSHS participation factors is also monitored with an aim to base the criterion on the free vibration characteristics of equipment. The a/l ratio is varied by gradually shifting the upper support of a simply supported uniform beam towards the lower support while keeping constant 1, Fig.7.1. The results of numerical study for various S2/S1
ratio are plotted in Figs. 7.2 through 7.6. The RMS modal mass versus nodal normal coordinates for EHS &
HSE method along with EHS & HSEH participation factors and modal frequency has been plotted in these
figures. It is worth noting that the variation of modal mass and not the increase in a/l ratio is
plotted on the x-axis. This is because the a/l ratio here is specific to a beam of uniform mass and
stiffness distribution whereas modal mass will be applicable to any equipment of non uniform mass and
stiffness distribution.

The Figs. 7.2 through 7.6 have been divided in three regions X, Y & Z. EHS method is conservative in
region X and unconservative in region Y irrespective of support group combination rule or a/l ratio.
Unconservation of EHS in region X is due to the reason that the source of frequency in this region is
from the overhanging masses, i.e., the segment of equipment where EHS method is unconservative.
Similarly, EHS method is conservative in region Y since the source of frequency in this region is from
the supported masses where EHS is over-conservative as compared to HSE method. However, in the region
Y, the source of frequency drifts from supported masses to the overhanging masses and the modal mass at
which EHS shows lower response as compared to HSE method depends on support group combination rule and
a/l ratio.

Above criterion is simple to apply since it is based on the physical characteristics of the first mode
of equipment vibration. If the first mode corresponds to overhanging masses, i.e., region Z of the
curve, in which case the sign of EHS modal participation factor will be same as the sign of node shape vector at the top of equipment, the analysis must be performed by HSE method. HSE method should
also be adopted if modal mass is less than 15% of the physical mass of the equipment. Since the
criterion relates effectiveness of overhanging masses with the modal mass, it is applicable to any
equipment of non uniform mass and stiffness distribution supported at any number of floors/elevations.

7 CONCLUSIONS

EHS is a conservative method for seismic analysis of equipment without overhang whereas it may severely
underestimate the response, as compared to the time history response, for the case of overhang equipment. However, HSE method appears to give conservative results for both class of equipment.

(ability to account a) magnification of response & b) contribution of antisymmetric modes resulting
from relative support motion are found to be the reason for unconservation of EHS method. A simple
criterion for selection of proper method, between EHS & HSE, for the analysis of overhang equipment
is developed. The criterion is based on correlation of modal mass with the nodal normal coordinate and
is applicable to generalized equipment of non uniform mass & stiffness distribution. It is shown that;
1) HSE method must be adopted if equipment first mode corresponds to vibration of overhanging masses.
2) HSE method should be adopted if the modal mass for the first mode is less than 15% of equipment

3) Algebraic support group combination appears to give realistic results for the analysis of equipment.

This is due to the dominant cantilever beam like behaviour of primary structure resulting in near
in-phase motion at equipment supports.

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FIG. 7.1 VARIATION OF z/L RATIO

FIG. 7.2 $S_2/S_1 = 1.00$

FIG. 7.3 $S_2/S_1 = 0.75$

FIG. 7.4 $S_2/S_1 = 0.50$

FIG. 7.5 $S_2/S_1 = 0.25$

FIG. 7.6 $S_2/S_1 = 0.08$

FIG. 7 EVALUATION OF CRITERION FOR SELECTION BETWEEN ERS & MSRS METHODS