A Procedure for Determining the SSE Response from the OBE Response

J. Curreri

Brookhaven National Laboratory, Department of Nuclear Energy, Building 129, Upton, New York 11973, U.S.A.

Abstract

Regulatory Guide 1.61 specifies the damping that should be used for all modes that are considered in an elastic spectral or time history dynamic seismic analysis of Seismic Category I components. Table 1 of R.G. 1.61 specifies damping values for dynamic analysis for two different earthquakes, the Safe Shutdown Earthquake and the Operating Basis Earthquake. The guide specifies that "... if the maximum stresses due to static, seismic and other dynamic loading are significantly lower than the yield stresses and 1/2 yield stress for SSE and 1/2 SSE respectively, in any structure a component damping values lower than those specified in Table 1 .... should be used .... to avoid underestimating the amplitude of vibration of dynamic stress." The guide requires that the appropriate damping values be used which reflect the state of stress that will be experienced by the equipment. In applying these values to the response of equipment, to an OBE and to an SSE, the selected damping should result in a dynamic response for the SSE that is greater than the response due to the OBE, all other factors being equal. The purpose of the statement in the guide is to note that at higher stress levels, the higher damping values could be used, but at lower stress levels, the lower values of damping should be used.

Current procedures that are used in implementing R.G. 1.61 frequently result in an OBE response that is greater than the SSE response. This is because the higher damping under the SSE is used at all stress levels, low as well as high. This is obviously not the intent of the intent of the Regulatory Guide.

A procedure has been developed which derives an expression relating the SSE response to the OBE response. Two factors are involved in the equation. The first involves the damping ratios for the SSE and OBE events and the second is the ratio between the levels of the OBE and SSE. The final result is

$$X_{0(SSE)} = A * X_{01(OBE)}$$

$$\text{where } A = \frac{1}{\sigma}\left[\frac{\lambda}{2} \pm \sqrt{\left(\frac{\lambda}{2}\right) - \sigma(1-\sigma)}\right]$$

$$\lambda = \frac{\text{peak time history SSE}}{\text{peak time history OBE}}$$

$$\sigma = \frac{\text{damping (SSE)}}{\text{damping (OBE)}}$$

1. Introduction

Fragility testing is different from proof testing. For proof testing, there is some distance, or margin, between the conditions induced by the loads and the conditions required for failure. For fragility testing there is no margin. Failure occurs at a point. As such, failure involves the characteristics of the excitation as well as the magnitude.

Fragility testing of equipment requires high levels of excitation. Seismic inputs at the SSE level and larger are generally needed. If information about the OBE response spectra is available, the problem is to determine the SSE spectra, given the OBE.

When the loads are specified, such as in a plant specific situation, there is no problem. Testing could be done simply by increasing the level of the excitation until failure occurs or until the excitation exceeds prescribed maximum probable levels.

But each kind of equipment has its own degree of fragility regarding seismic excitation. Some are relatively rugged, and so the level of seismic excitation will not matter too much. For others, the test level will be crucial. Testing rugged equipment for fragility could require very high levels of excitation. This could be impossible, or at least very costly, to produce with existing equipment. However, there is always some practical cut-off level of excitation beyond which it can be said that the equipment will not fail in a seismic environment. The question is, what is that level? If the fragility level of the equipment is to be determined on a generic basis, an added complexity is introduced into this question.

A generic floor response spectra was available for the Operating Basis Earthquake (OBE), [1]. The spectra were developed as a maximum response situation for equipment in any nuclear power plant which was located on any type of soil. With this information, it was required to obtain a maximum generic floor response spectra for running fragility tests of electric motors.

Actual structure or equipment failure is normally associated with large seismic excitation which is at, or beyond, the level of the Safe Shutdown Earthquake (SSE) rather than the OBE. The current procedure of using a higher damping valve for the SSE is not valid for this purpose of failure determination since the response is sometimes lower for the SSE.

Regulatory Guide 1.61 specifies the damping that should be used for all modes that are considered in an elastic spectral or time history dynamic seismic analysis of Seismic Category I components. Table 1 of R.G. 1.61 specifies damping values for dynamic analysis for two different earthquakes, the Safe Shutdown Earthquake and the Operating Basis Earthquake. The guide specifies that ".... if the maximum stresses due to static, seismic and other dynamic loading are significantly lower than the yield stresses and 1/2 yield stress for SSE and 1/2 SSE respectively, in any structure a component damping values lower than those specified in Table 1 .... should be used .... to avoid underestimating the amplitude of vibration of dynamic stress." the guide requires that the appropriate damping values be used which reflect the state of stress that will be experienced by the equipment. The purpose of the statement in the guide is to note that at higher stress levels, the higher damping values could be used, but at lower stress levels, the lower values of damping should be used.

The response of equipment and structures with SSE loading should be greater than the response for the OBE case. Nevertheless, the design codes and procedures ae conservatively stipulated to assure the safe design of these structures. The current procedures are therefore acceptable on the basis of the conservative treatment of the loads and the damping values.

For the fragility testing of electric motors under a generically obtained loading, a more rational description between the responses under OBE and SSE loading was needed. Accordingly, an easy to use, simple relation between a generic OBE and SSE loading was looked for.

2. Response Spectra for Different Loading and for Different Damping

The generic curves were obtained with 5-percent structure damping and with 2-percent equipment damping. These are OBE values. A procedure was developed to use these spectra for other damping values, such as those associated with an SSE event on a larger load. An energy approach, based upon a steady state situation, was used to establish the relationship.

For a steady state sinusoidal force on a one-degree of freedom damped system, the energy input by the force is given by

$$E_i/\text{cycle} = \int F dx = \int_0^{\frac{2\pi}{\omega}} F \left(\frac{dx}{dt} \right) dt \qquad (1)$$

For $F = F_0 \text{Sin}\ (\omega t + \phi)$ and $X = X_0\ \text{Sin}\ \omega t$, the integral in eq. (1) becomes

$$E_i/\text{cycle} = \pi F_0 X_0 \ (\text{maximum}) \qquad (2)$$

Similarly for visious damping, the energy dissipated is

$$E_d/\text{cycle} = \pi c \omega X_0^2 \qquad (3)$$

Equating these two, the equilibrium amplitude becomes

$$X_{01} = \frac{F_o}{C_1 \omega} \qquad (4)$$

Equations (2) and (3) are plotted in Fig. 1. The equilibrium amplitude, designated as X_{01} in equations (4), is shown at point A.

If the magnitude of the input is multiplied by a factor λ, for the same damping, the equilibrium amplitude would be established at point B. However, if damping is also changed by a factor λ, then a new equilibrium amplitude would be obtained, as shown at point C.

But for this case, X_{02} is less than X_{01} and so higher damping value cannot be justified. This is the type of procedure which could result in a lower response for a larger input because it misuses the value of the damping constant. Until the response is at least as large as X_{01}, the same value of damping should be maintained. When the response due to a larger excitation exceeds X_{01}, then the higher value of damping stipulated in the Regulatory Guide 1.61 may be used. This procedure assumes that a high value of stress is developed at the displacement X_{01}, and so the higher damping constant is valid.

A rational relationship could be obtained if we express this understanding of the damping values associated with the responses. Up to a response of X_{01} in Fig. (1), a damping of C_1 will be used. This corresponds to the response level of the OBE. Above this response a value of $\gamma\ C_1$ will be used. This is the region of the SSE which is larger than the OBE of a factor of λ or SSE = λ (OBE). Equating the energy dissipated and the energy input, for steady state conditions,

$$\pi c_1\omega X_{01}^2 + \pi(\gamma c_1)\omega X_0^2 - \pi(\gamma c_1)\omega X_{01}^2 = \pi\lambda F_o X_o \quad (5)$$

but

$$X_{01} = \frac{F_o}{c_1\omega}$$

so that

$$c_1\omega\left(\frac{F_o}{c_1\omega}\right)^2 + (\gamma c_1)\omega\left[X_o^2 - \left(\frac{F_o}{c_1\omega}\right)^2\right] = \lambda F_o X_o \quad (6)$$

or

$$\gamma c_1\omega\, X_o^2 - \lambda F_o X_o + \frac{F_o^2}{c_1\omega}(1-\gamma) = 0$$

Solving for X_0

$$X_0 = \frac{\lambda F_o \pm \sqrt{(\lambda F_o)^2 - 4(\gamma c_1\omega)\quad\frac{F_o^2}{c_1\omega}(1-\gamma)}}{2(\gamma c_1)\omega} \quad (7)$$

So that

$$X_0 = \frac{F_o}{\gamma c_1\omega}\left[\frac{\lambda}{2} \pm \sqrt{\left(\frac{\lambda}{2}\right)^2 - \gamma(1-\gamma)}\right] \quad (8)$$

or

$$X_0 = A\left(\frac{F_o}{c_1\omega}\right) = AX_{o1} \quad (9)$$

where

$$A = \frac{\frac{\lambda}{2} + \sqrt{\left(\frac{\lambda}{2}\right)^2 - \gamma(1-\gamma)}}{\gamma} \quad (10)$$

or

$$A = \frac{\lambda}{2\gamma} + \sqrt{\left(\frac{\lambda}{2\gamma}\right)^2 + \left(1 - \frac{1}{\gamma}\right)} \quad (11)$$

Equation (9) expresses the equilibrium in terms of a factor times the response at the OBE level with a damping of C_1.

As an example, this equation was applied to the structural response as well as to the equipment response for an SSE. Each is treated as a separate one degree of freedom system. The results are given in Figure 2, as they relate to the GFRS for equipment involved in a safe shutdown earthquake. For the SSE, damping is taken as 7 percent for the structure and 3 percent for the equipment as compared to the OBE values of 5 and 2 respectively. The SSE peak time history is taken as twice the OBE peak. The response of the structure is used as the input to the equipment. As the factors in Figure 2 show, the maximum equipment response for a ground SSE is 1.33 times the OBE response, as shown by the constant A_2.

The generic floor response spectra were obtained using OBE damping values. They were determined to be maximum response magnitudes, both in terms of frequencies as well as in magnitude. Equation 11 could be used to obtain the multiplying constant, A, for other loads and for other damping values. The derivation was based upon the use of a steady-state, rather than a transient situation. Fragility testing could use the resulting floor response spectra as a bounding description of the maximum floor response. This describes the maximum relevant generic earthquake response for any equipment, in any nuclear power plant which is located on any type of soil. The fragility of equipment, on a generic basis, could be determined within this level. If failure cannot be induced in the equipment up to this level, then the equipment is not fragile to seismic loads.

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NOTICE

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission, Washington, DC. The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the United States Nuclear Regulatory Commission or organizations of authors.

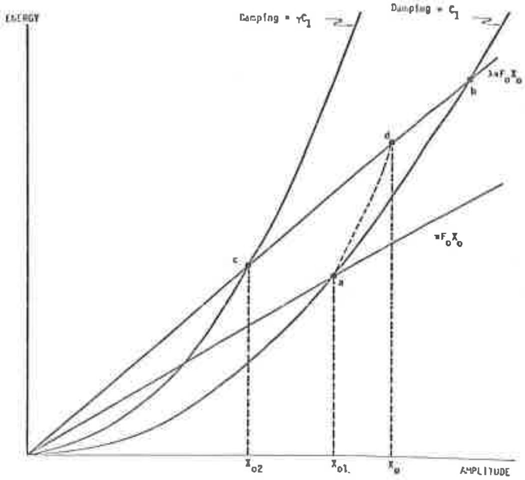
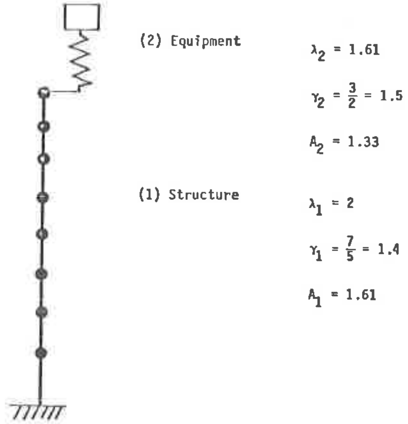


Fig. 1. Response vs. Damping Energy Dissipation for a Single Degree-of-Freedom System



$\lambda_2 = 1.61$

$\gamma_2 = \frac{3}{2} = 1.5$

$A_2 = 1.33$

$\lambda_1 = 2$

$\gamma_1 = \frac{7}{5} = 1.4$

$A_1 = 1.61$

Fig. 2. Evaluation of Magnification Constant A for Structure and Equipment