INSTANTANEOUS RESPONSE SPECTRUM IN SEISMIC TESTING OF NUCLEAR POWER PLANT EQUIPMENT

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SUMMARY

Seismic response spectra, as used in seismic analyses, give the maximum responses of single degree of freedom oscillators without consideration of the different time in the seismic time history at which each of the maximum responses occur. For response spectrum seismic analysis, the use of time-independent maximum responses is appropriate. The time dependence is considered in a statistical manner, for multi-degree of freedom systems, usually by combining the modal effects by the square root of the sum of the squares. For seismic testing of electrical equipment, IEEE Std. 344-1975 makes use of the response spectrum to define the input motion of the shake table. One of the basic requirements is that the test response spectrum (TRS), that is, the response spectrum produced by the shake table motion, should envelop the required response spectrum (RRS) calculated from the building analysis at the support point of the equipment being tested. This enveloping requirement is in part due to the desire of generating a test motion which simulates the seismic motion in frequency content, as well as amplitude, so that multiple frequencies of the equipment being tested are excited simultaneously. However, since the RRS enveloping with the TRS is to be obtained with standard response spectra, independent of time, it is not obvious that the enveloping is also satisfied at a particular time so that the multiple frequency effects are indeed simultaneous. This may be investigated by comparison of the enveloping of TRS and RRS derived at particular times obtained with time histories whose standard TRS envelops the RRS.

This paper presents the concept of instantaneous response spectrum (IRS) as the response of single degree of freedom oscillators at a particular time. It demonstrates that a shake table random motion whose standard TRS envelops the RRS does not necessarily satisfy the enveloping requirement instantaneously. That is, any one (or more) instantaneous required response spectrum (IRRS) is not enveloped by any instantaneous test response spectrum (ITRS). Response spectra from different time histories, including single frequency sine beat motion used in resonance testing, are compared for enveloping with maximum response and with the actual response at particular times. These comparisons are given for the enveloping of RRS and IRRS derived with a time history response calculated at a particular building elevation of a nuclear power plant. For the test motion, several of the most severe ITRS derived with a modified EL Centro motion and with a sine beat motion with ten cycles per beat were used. It is shown that although the TRS with the modified EL Centro motion enveloped the given RRS, the selected modified EL Centro ITRS did not envelop the corresponding IRRS. With the sine beat motion, even though the TRS did not fully envelop the given RRS, the resulting sine beat ITRS did not require a larger factor for full IRRS enveloping than those of the modified EL Centro motion.

1.0 INTRODUCTION

Seismic response spectra which are derived for use in response spectrum analysis are also being utilized to define the test motion for seismic testing of nuclear power plant equipment. For seismic analysis, the use of the time-independent maximum responses given by these standard response spectra is appropriate, since the time dependence is usually considered by combining the modal effects by the square root of the sum of the squares. For seismic testing of electrical equipment, a basic criterion of IEEE Std. 344-1975 [1] is that the test response spectrum (TRS) should envelop the required response spectrum (RRS). The TRS is the response spectrum produced by the shake table motion, and the RRS is the response spectrum calculated from the building analysis at the support point of the equipment being tested. This enveloping criterion is to generate a test motion which simulates the calculated seismic motion in frequency content and amplitude so that multiple frequencies of the tested equipment are excited simultaneously. For this multiple frequency testing, a synthetic motion is developed such that its response spectrum envelops the RRS and this motion is used as the shake table motion.

Since the enveloping of the RRS with the TRS is done with the time-independent response spectra, the enveloping criterion may not really ensure that the full effects of simultaneous multiple frequency excitations are obtained. This is because the maximum responses at different frequencies generally occur at different times. That is, the RRS enveloping with the TRS does not ensure that the enveloping is also satisfied with response spectra which give responses (not all maximum responses) at particular time. To investigate this condition, it is necessary to compare response spectra derived at particular times, that is, instantaneous response spectra. The times at which the instantaneous RRS (IRRS) and the instantaneous TRS (ITRS) are derived need not be the same. Neither is it necessary that the enveloping be obtained with IRRS and ITRS whose responses are maximum for the same oscillator period. However, this is a convenient condition and in most cases better enveloping is obtained. The comparison is made to determine if there is any one (or more) IRRS which is not enveloped by any ITRS, using motions whose TRS envelops the RRS.

In this study, three motion time histories were used. A response motion calculated at a particular building elevation of a nuclear power plant was used as the required motion. For the test motions, a synthesized time history and a sine beat motion were used. The synthesized time history was derived such that its response spectrum enveloped the RRS, whereas the response spectrum of the sine beat did not fully envelop the RRS. A screening analysis was performed to identify four of the most encompassing ITRS of the synthesized time history and sine beat motions for comparison with the IRRS of the required motion. It is shown that none of the four ITRS fully envelop the IRRS even though the TRS of the synthesized time history fully enveloped the RRS.

2.0 DERIVATION OF MOTIONS AND RESPONSE SPECTRA

The required seismic motion used for the enveloping comparison was taken from the results of the containment structure dynamic analysis of a nuclear power plant. The response motion at a lower elevation on the containment was chosen since it was of a relatively wide band shape. This motion has a maximum acceleration of 0.408g and a peak response acceleration of 1.884g, for 5% of critical damping, at a period of 0.420 sec. The duration of the motion used was 10 sec. and the time in the accelerogram at which the peak response acceleration occurs is 3.2 sec.

The synthesized time history test motion consists of a modified El Centro N-S accelerogram of 20 sec. duration. The maximum acceleration of the original accelerogram was raised to 0.480g, along with other modifications in frequency content and amplitude, to make its response spectrum fully envelop the RRS. The peak response acceleration of this test motion, also for 5% of critical damping, was 1.995g at periods of 0.430 and 0.440 sec. The time in the accelerogram at which the peak response acceleration occurs is 2.710 and 2.720 sec.

The sine beat test motion was represented with a sine beat containing 10 cycles of 0.420 sec. period motion, a maximum acceleration of 0.408g and a duration of 4.2 sec. Both the period and acceleration values were chosen to make the sine beat equivalent to the nuclear power plant motion in predominant frequency content and maximum acceleration. This sine beat motion is shown on Fig. 1. The 5% of critical damping peak response acceleration is 3.092g which occurs at 3.141 sec. in the beat.

The superposition of the standard response spectra (RRS and TRS) of all three motions is shown on Fig. 2. Fig. 2(a) shows the full enveloping of the nuclear power plant RRS with the modified El Centro TRS. This enveloping is conservative and no attempt was made to optimize the motion for closer enveloping. The comparison between the nuclear power plant RRS and the 10 cycle beat TRS is shown on Fig. 2(b). It is seen that the 10 cycle beat TRS is quite adequate for maximum response (3.092g Vs. 1.884g) but, due to its narrow bandwidth, it fails to fully envelop the RRS. A sine beat with a smaller number of cycles would have given a better enveloping because of lower maximum response acceleration and broader spectrum shape. However, the 10 cycle beat was chosen to obtain a more meaningful comparison of ITRS with broad band multiple frequency and narrow band single frequency motions.

The response spectra were calculated with standard computer methods, as given in [2]. The sine beat motion was expressed in terms of acceleration by

$$\ddot{x}_b = a\left[\sin \omega_b t \sin(\omega_b t/2n)\right] \qquad (1)$$

which reduces to the sum of two waves with frequencies of

$$f_{b1} = f_b(1 + 1/2n) \text{ and } f_{b2} = f_b(1 - 1/2n) \qquad (2)$$

where:

$\ddot{x}_b$ = acceleration of motion within the beat

a = maximum acceleration of beat motion

ω_b, f_b = frequency of motion within the beat

n = number of cycles within the beat

t = time

With the 0.420 sec. period of the beat motion (f_b = 2.381 Hz) and with n = 10, f_{b1} = 2.500 Hz. and f_{b2} = 2.262 Hz.

3.0 COMPARISON OF INSTANTANEOUS RESPONSE SPECTRA

An example of an instantaneous response spectrum is shown on Fig. 3. This figure shows the IRRS of the nuclear power plant motion derived at the time (3.2 sec.) when the response to this motion was maximum (1.884g) for the 0.420 sec. period oscillator. The

RRS of the same motion is also plotted on this figure to compare the two different spectra shapes. The IRRS response is equal to that of the RRS only at and close to the period and associated time at which it was derived. For all other periods, the IRRS response is much lower than the RRS since for these other periods the responses are maximum at times other than 3.2 sec. in the accelerogram.

The next four figures show the enveloping comparison of the modified El Centro and 10 cycle beat ITRS with IRRS of the nuclear power plant motion. All the IRRS were derived at times of maximum response for different oscillator periods. From a screening analysis, the best modified El Centro ITRS which came closer to envelop the IRRS occurred at times of maximum response for the same oscillator periods of the IRRS. Those of the 10 cycles beat motion occurred randomly at different times and not at times when the response of any of the oscillators was maximum. Further search for optimum 10 cycle beat ITRS could produce better enveloping than that presented. Both the modified El Centro and 10 cycle beat ITRS failed to fully envelop the IRRS.

Figure 4 shows the ITRS enveloping of the IRRS of Fig. 3. The chosen modified El Centro ITRS for this enveloping is shown on Fig. 4(a) and was derived at the time (2.7 sec.) when the 0.420 sec. period gave maximum response. It is seen that the enveloping is necessarily met at the 0.420 sec. period because the modified El Centro TRS fully enveloped the RRS. However, the enveloping is not complete for all periods considered. The largest full enveloping descrepancy occurs at a period of 0.54 sec. where the ITRS response is very small relative to that of the IRRS. A factor of about 18 is estimated to be required for full enveloping. Figure 4(b) shows the 10 cycle beat ITRS used for the same IRRS enveloping. This 10 cycle beat ITRS was derived at 1.695 sec. in the beat and the responses at this time are not maximum for any oscillator period calculated. Full enveloping is also not achieved and the largest factor needed for full enveloping is 4.1 at a period of 0.27 sec.

Figure 5 compares the enveloping of the nuclear power plant IRRS derived at 2.640 sec. in the accelerogram at which time the 0.550 sec. period response was maximum. The modified El Centro ITRS for the same period and at 2.360 sec. in the accelerogram failed the full enveloping by a factor of about 13 at a period of 0.22 sec., as shown on Fig. 5(a). The 10 cycle beat ITRS enveloping comparison is shown on Fig. 5(b). This ITRS was derived at 2.395 sec. in the beat and requires a maximum factor of 2.3 at a period of 0.42 sec. for full enveloping.

Figures 6 and 7 show two more enveloping comparisons with IRRS of the nuclear power plant motion at times of 2.695 and 2.670 sec., respectively. The maximum responses occurred at two periods of 0.260 and 0.290 sec. for the 2.695 sec. IRRS, and also at two periods, 0.075 and 0.190 sec.,for the 2.670 sec. IRRS. Figure 6(a), with a modified El Centro ITRS derived at 2.210 sec. in the accelerogram (maximum response at period of 0.260 sec.), shows that the largest factor required for full enveloping is about 15 at a period of 0.22 sec. Figure 6(b) shows the enveloping with a 10 cycle beat ITRS derived at 1.995 sec. in the beat. Its largest enveloping factor is 2.3 at a period of 0.60 sec. Figures 7(a) and 7(b) give the same type of comparison with a modified El Centro and 10 cycle beat ITRS derived at 1.985 and 2.395 sec., respectively. The maximum response for the modified El Centro ITRS occurred at the 0.190 sec. period. The largest factors for full enveloping were about 9 for the modified El Centro ITRS, and 2.1 for the 10 cycle beat ITRS, both at periods of 0.60 sec.

All the 10 cycle beat ITRS were obtained from one beat with a frequency of motion within the beat of 1/0.420 Hz. However, in sine beat resonant testing, the frequency of the test motion is changed to correspond to each of the natural frequencies of the equipment being tested found from a resonance search. This means that sine beat ITRS with different frequency of motion within the beat can be used for a better enveloping comparison with the IRRS. An example of this is shown on Fig. 8. This figure shows the enveloping of the nuclear power plant IRRS of Fig. 4(b) with a 10 cycle beat ITRS derived at 2.205 sec. in the beat but with a period of the motion within the beat of 0.520 sec. instead of 0.420 sec. The largest factor for full enveloping is now 2.0 at a period of 0.4 sec., whereas a factor of 4.1 was required in the Fig. 4(b) enveloping with the 0.420 sec. period sine beat motion.

4.0 CONCLUSIONS

The concept of instantaneous response spectra has been presented to show that even though the response spectrum of a required motion is fully enveloped by that of a synthetic test motion, this enveloping is not achieved with the actual response at any particular time. A modified El Centro motion was used as one of the test motions whose standard response spectrum conservatively enveloped that of a required nuclear power plant motion. However, none of the four modified El Centro ITRS chosen fully enveloped the nuclear power plant IRRS. An instantaneous full enveloping deficiency was also obtained with a 10 cycle beat test motion. In the case of the 10 cycle beat, its standard response spectrum did not originally envelop that of the nuclear power plant motion. Therefore, better instantaneous response spectra enveloping could have been obtained if the 10 cycle beat test motion had been modified initially such that its standard response spectrum would have fully enveloped that of the nuclear power plant motion.

The purpose of this paper is not to recommend that for seismic testing, instantaneous response spectra be used for the enveloping criterion. This, obviously, is impractical. It is to: 1) introduce the idea of instantaneous response spectrum so that it may be considered as desired in the development of the test motion, and 2) show that a test motion derived solely on its RRS enveloping capability may not give the desired simulation of the seismic motion which was expected. Furthermore, it is believed that the adequacy of the test motion does not necessarily depend on its capability to envelop the RRS but on its severity at the natural frequencies of the equipment being tested. Resonance testing, as with motion such as sine beat, can produce accelerations on vital parts of a piece of equipment well above those expected to be produced by the calculated seismic motion, as was shown on Fig. 2(b).

REFERENCES

[1] IEEE Std 344-1975 "IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations", Institute of Electrical and Electronic Engineers, January 31, 1975.

[2] Morrone, A., "Seismic Vibration Testing with Sine Beats", <u>Nuclear Engineering and Design</u> 00, 344-356 (1973).

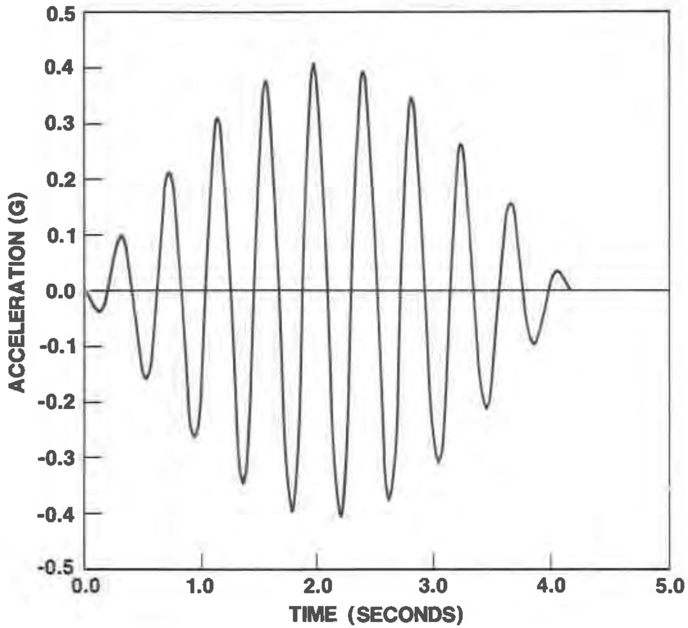

Figure 1 - Sine Beat Test Motion with 10 Cycles per Beat

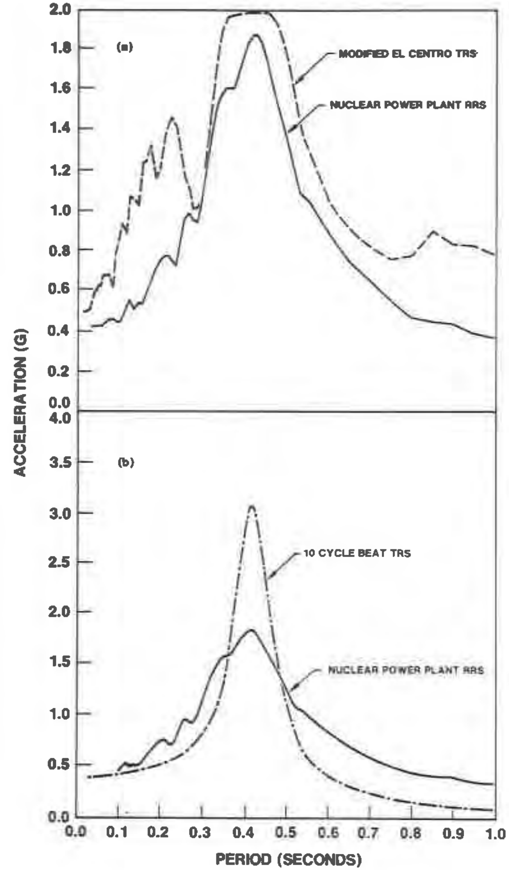

Figure 2 - Enveloping of Nuclear Power Plant RRS (5% Damping) (a) with Modified El Centro TRS; (b) with 10 Cycle Beat TRS

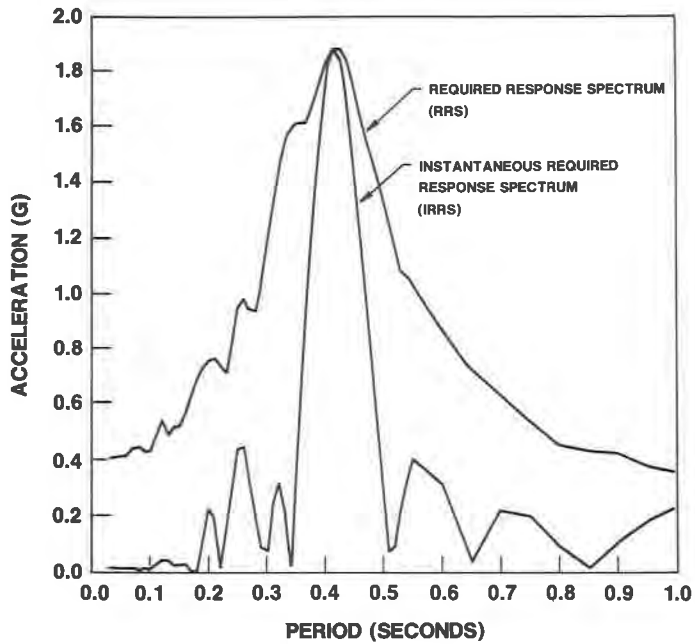

Figure 3 - RRS and IRRS of Nuclear Power Plant Motion (5% D

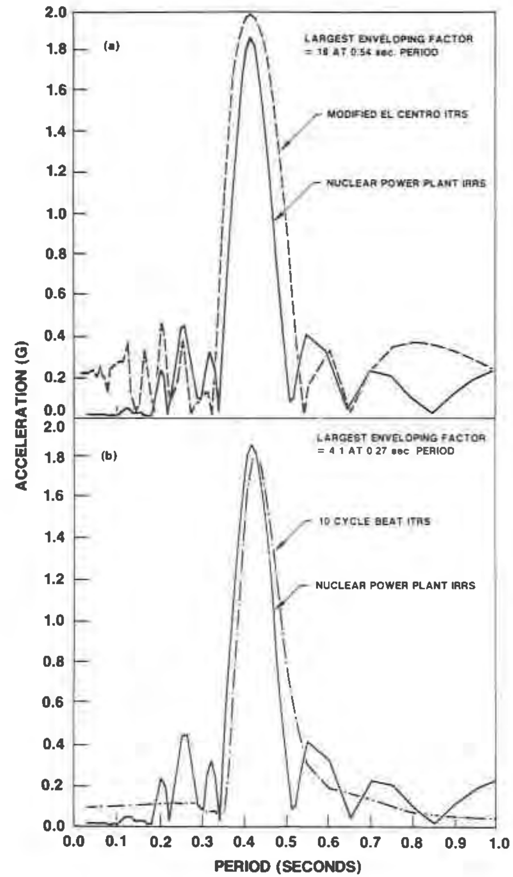

Figure 4 - Enveloping of Nuclear Power Plant IRRS at 3.2 sec.
(5% Damping)
(a) with Modified El Centro ITRS at 2.7 sec.
(b) with 10 Cycle Beat ITRS at 1.695 sec.

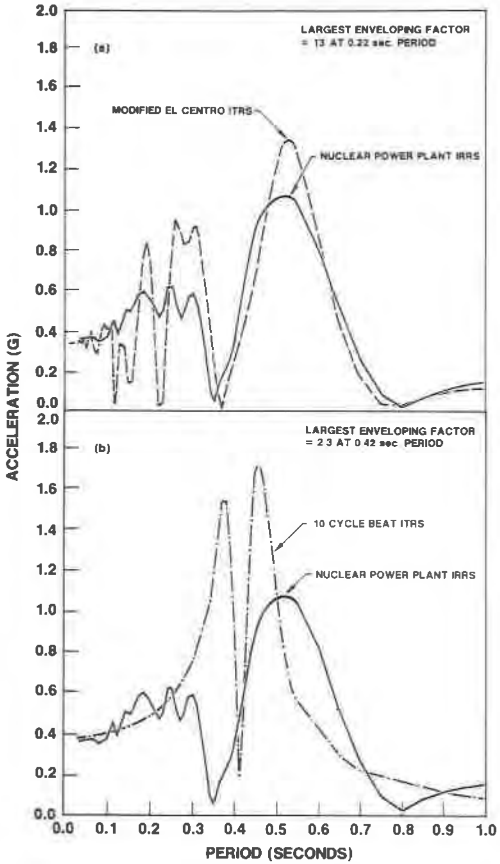

Figure 5 - Enveloping of Nuclear Power Plant IRRS at 2.
(5% Damping)
(a) with Modified El Centro ITRS at 2.360 sec.
(b) with 10 Cycle Beat ITRS at 2.395 sec.

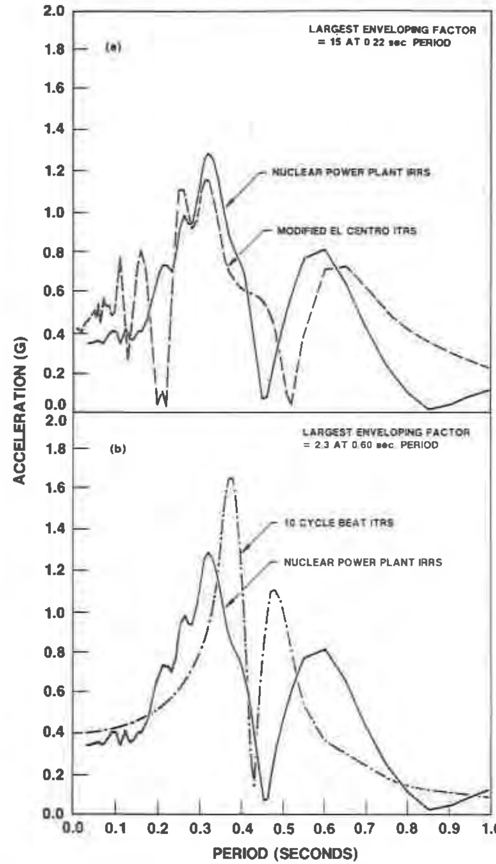

Figure 6 - Enveloping of Nuclear Power Plant IRRS at 2.695 sec.
(5% Damping)
(a) with Modified El Centro ITRS at 2.210 sec.
(b) with 10 Cycle Beat ITRS at 1.995 sec.

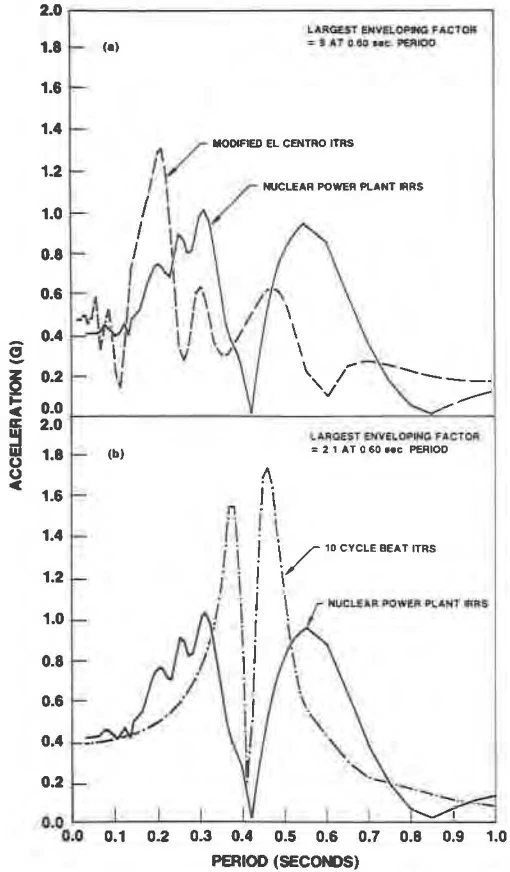

Figure 7 - Enveloping of Nuclear Power Plant IRRS at 2.670 sec. (5% Damping)
(a) with modified El Centro ITRS at 1.985 sec.
(b) with 10 Cycle Beat ITRS at 2.395 sec.

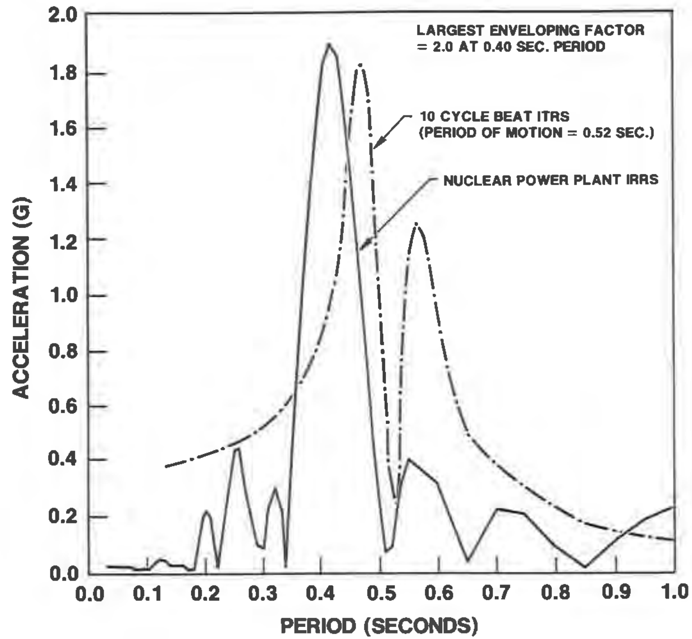

Figure 8 - Enveloping of Nuclear Power Plant IRRS at 3.2 sec. with 10 Cycle Beat ITRS at 2.205 sec., and Period of motion within Beat of 0.52 sec. (5% Damping)