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SEISMIC TEST SPECTRA FOR COMPOSITE MULTI-SITE BROADBAND REQUIRED RESPONSE SPECTRA

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ABSTRACT

The seismic design for new generation nuclear plants entails enveloping the conditions from several candidate plant sites to achieve a single generic design. This idea has been extended to the generation of In-Structure Response Spectra (ISRS) and generic qualification of plant components and equipment, by considering Required Response Spectra (RRS) that envelope all individual site-specific RRS. This approach achieves substantial economies through use of a single qualification effort, based on the enveloping RRS for qualification of the components and equipment at all sites. Such enveloping spectra are valid for response spectrum analyses, but may be unconservative when represented by artificial time histories for subsequent time history analysis or in-equipment spectra generation. The time histories compatible with the enveloping spectra may be deficient in energy at the frequencies of individual site spectra, producing in-equipment motions which are also deficient in energy content at individual site peak spectral frequencies. Such deficiency is dependent on the extent to which the comprising enveloped spectra are broad-banded. In lieu of an approach which qualifies to the individual site spectra, this investigation develops and demonstrates a method to appropriately modify the enveloping spectrum to account for site-specific resonance effects. The method characterizes the enveloping spectrum as a random, broad-banded input and the site spectra as sine beat motions. Based on dynamic response studies, recommendations for modification of the enveloping design spectrum are provided.

INTRODUCTION

For cost and efficiency, an approach considered for the seismic qualification of equipment in some new generation nuclear power plants is the use of composite floor response spectra which envelope the floor response spectra for multiple sites. The resulting enveloping spectra, while sufficient in spectral amplitude at all frequencies, are more broad-banded than the individual site spectra and have lower energies over the specific bandwidths representative of those individual site spectra. This raises a question, important for analysis as well as testing, as to whether the combined resonant and off-resonant amplification of the broad-banded enveloping spectra are sufficient to represent amplification at resonance of the site spectra. Since the enveloping spectral accelerations are of sufficient amplitude, this consideration would not affect a response spectrum analysis (RSA). However, if a spectrum compatible time history were to be developed from the enveloping spectrum and then used subsequently to develop in-structure response spectra, say, within a control panel, or on a platform, then the concerns are the same as those for testing: is there sufficient energy in the waveform to capture individual site spectra resonant amplification behaviour? Direct verification of these concerns can be performed by generating spectra from the composite envelopes and comparing them with the spectra from the individual sites.

An analytical representation of the enveloping and site spectra is shown in Fig. 1. To implement this study, time histories compatible with acceleration response spectra could be developed, and system responses generated and studied. Alternatively, response spectra could be converted to power spectral densities (PSDs) and the algebraic methods for PSDs could be used to establish relationships and

conclusions. Both of these approaches are deemed relatively intensive in numerical calculation compared to more simplified representations and relations which enable general, but sufficiently quantitative conclusions to be reached. Such simplified representations are provided by approximating seismic base motions as impulses (discussed below) in the case of broad-banded motions and as sine beats in the case of narrow-banded motions.

METHODOLOGY

It is assumed, for simplicity, that the site spectra result from sine beat motions and that the relatively broad-banded composite envelope is flat over a wide range of frequencies. Actual nuclear power plant composite (enveloping) spectra are narrower, but the broad characterization is appropriate first because amplification effects at and near resonance are considered and second because a very broad spectral bandwidth is mathematically convenient. Various spectral bandwidths are considered for the site spectra (Fig. 2), so that conclusions can be reached based on the degree to which the site spectra are broad-banded. For both the broadband envelope spectrum and the site spectra produced by sine-beat motions, readily integrated closed form equations are available to generate the ISRS. Time history motions producing flat spectra and definitions of sine beat motions compatible with given narrow-banded spectra are given in the next sections.

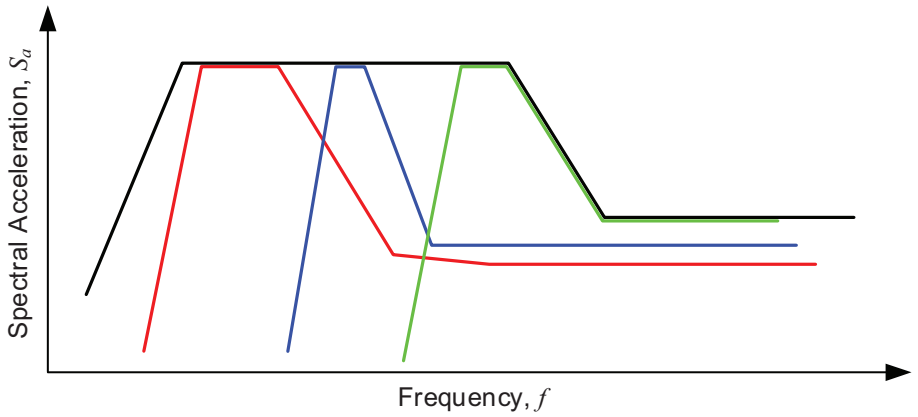


Figure 1. Enveloping of Site Spectra with Composite Broad-banded Spectrum.

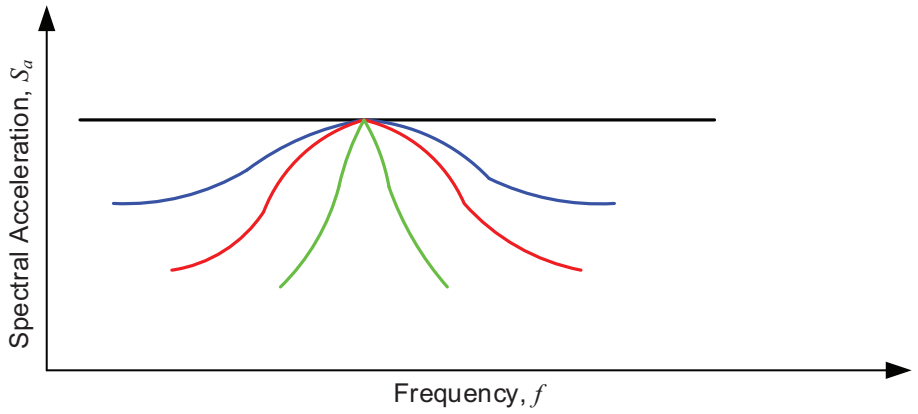


Figure 2. Sine Beat Spectra of Various Bandwidths and Idealized Enveloping Composite Spectrum.

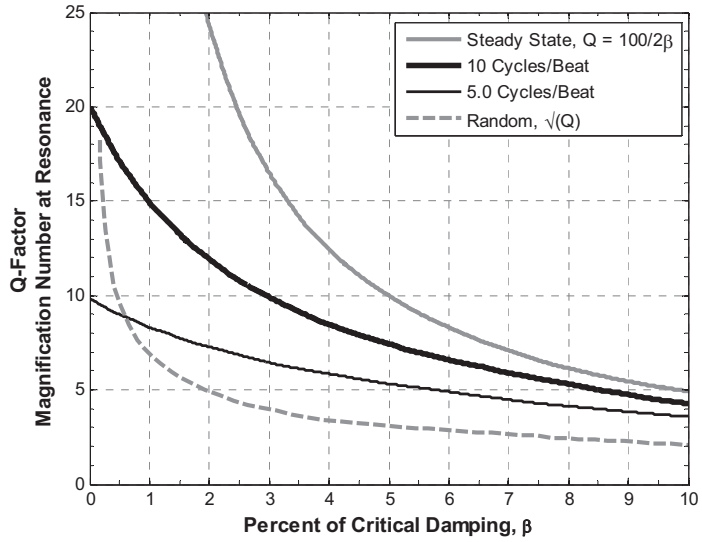


Figure 3. Q-Factor for Sine Beat Motion Amplification at Resonance (adapted from Fischer, 1972).

Sine beat motions are modulated sinusoidal motions (see Fig. 6) which are similar to the response motions that harmonic oscillators experience under seismic excitation. The modulation produces a more realistic amplification and damage than does the unmodulated pure harmonic input, and this explains the extensive use of sine beat motions in seismic and vibratory testing. The response spectrum for a given sine beat motion is characterized by a Q-factor, magnification number at resonance, which represents the damping-dependent ratio of peak spectral acceleration to the zero period acceleration (ZPA) as shown in Fig. 3. This Q-factor, together with a damping ratio (β) and number of cycles per beat (N) can be used to represent response spectra with a range of spectral bandwidths from narrowband to relatively broadband as shown in Fig. 5. Clearly, sine beat motions with a large number of cycles per beat will have narrower bandwidths since more successive peaks of the input beat motion are at a higher relative acceleration, thereby accentuating resonant response amplification. The capability of sine beat motions to represent a range of spectral shapes together with their convenient analytical definitions makes them ideal for this investigation. A sine beat motion, *ü(t)*, is defined by

$$\ddot{u}(t) = -G\left(\sin\left[\left(\frac{\omega_1+\omega_2}{2}\right)t\ \right]\cdot\ \sin\left[\left(\frac{\omega_1-\omega_2}{2}\right)t\ \right]\right) \tag{1}$$

where,

$\left(\frac{\omega_1+\omega_2}{2}\right)$ = angular natural frequency of waveform

$\left(\frac{\omega_1-\omega_2}{2}\right)$ = angular natural frequency of envelope (2 beat pulses)

$F_i\ = \frac{\omega_i}{2\pi}$ = natural frequency

G = peak acceleration.

Detailed discussions on the use of sine beat to represent seismic base motions are provided in Fischer (1972), Marrone (1973), and IEEE-344 (2004).

REPRESENTATION OF THE BROAD-BANDED SPECTRUM BY A RECTANGULAR PULSE

It is clear by definition, that a strictly broad-banded seismic response spectrum is one for which the acceleration from the base motion, for every frequency of harmonic oscillator (at a fixed value of damping), is constant. A conventional earthquake time history, which we think of and characterize as having random multi-frequency content with energy over a range of frequencies less than the ZPA cutoff frequency, cannot represent such a condition, since softening of a rigid system (which responds at the ZPA frequency) will result in amplification of the response over the ZPA response, and thereby a non-uniform spectrum, by definition. However, base motions characterized by pulses, can represent close and useful approximations for "uniform seismic spectra". Step functions accelerate zero-damped harmonic oscillators to twice the corresponding static response regardless of the oscillator frequency. Consider the undamped base motion dynamic equilibrium equation,

$$m\ddot{x}(t) + kx(t) = F(t) = -m\ddot{u}(t) \tag{2}$$

where $\ddot{u}(t)$ is an instantaneously applied (Heaviside step function) base motion acceleration. The unamplified or static relative displacement response is $m\ddot{u}_{max}/k$ and the amplified displacement response is $2m\ddot{u}_{max}/k$. The acceleration corresponding to the amplified displacement response is $[2m\ddot{u}_{max}/k]\omega^2 = 2\ddot{u}_{max}$, which is independent of frequency. Fig. 2.9 of Biggs (1964) shows clearly that when the pulse rise time is less than about one-quarter of the system period, the dynamic response will be twice the static response.

In the actual application of a step function to represent base motion input, damping must be considered. For lightly damped systems (1% to 5%), damping has little effect, because response to an impulse occurs early enough that the effect of damping does not have enough time to influence the response. Actual amplification of a damped system, for the range of parameters considered in this investigation, is not less than 1.9. Fig. 5 shows results of the step function approximation for a broad-banded spectrum. This kind of non-characteristic earthquake motion raises the concern as to what physical earthquake phenomenon or condition it might represent. A rectangular pulse of finite duration can certainly be associated with acceleration inputs resulting from an earthquake fault/dislocation. Since, over the frequency ranges of interest, the peak spectral responses due to such impulses are nearly the same as those for a step function (peak response occurs early in the system time history response), the broad-banded step function spectrum can be considered to represent a fault/dislocation condition. Various impulse representations are commonly used to simulate near-fault seismic motions (Xu and Xie, 2006).

PRIMARY AND SECONDARY SYSTEM RESPONSE SPECTRA

The nuclear power plant systems of interest for this investigation are those which can be represented by a pair of lightly damped, cascaded, dynamically uncoupled harmonic oscillators, excited by a base motion acceleration $\ddot{u}(t)$ as shown is Fig. 4. The decoupling, or elimination of dynamic feedback from the secondary system (m_S, k_S) to the primary system (m_P, k_P) is accomplished by $m_P >> m_S$. Many power plant systems are represented by this modelling concept. For example, for the horizontal response of a floor mounted electrical cabinet housing instrumentation on a panel face, the primary system is defined by the cabinet global cantilever stiffness and associated effective mass, and the secondary system can be defined by the local mass and stiffness associated with the panel face drumming. To qualify the devices mounted on the panel, ISRS due to in-cabinet motions $\ddot{x}_P(t)$ are needed. Another example is instrumentation mounted on a heavy piece of equipment such as a steam generator, or instrumentation mounted on an emergency diesel generator. In all of these examples, the secondary system has small mass compared to a base motion excited primary system, and ISRS are required to be generated for qualification of the attached instrumentation or secondary system.

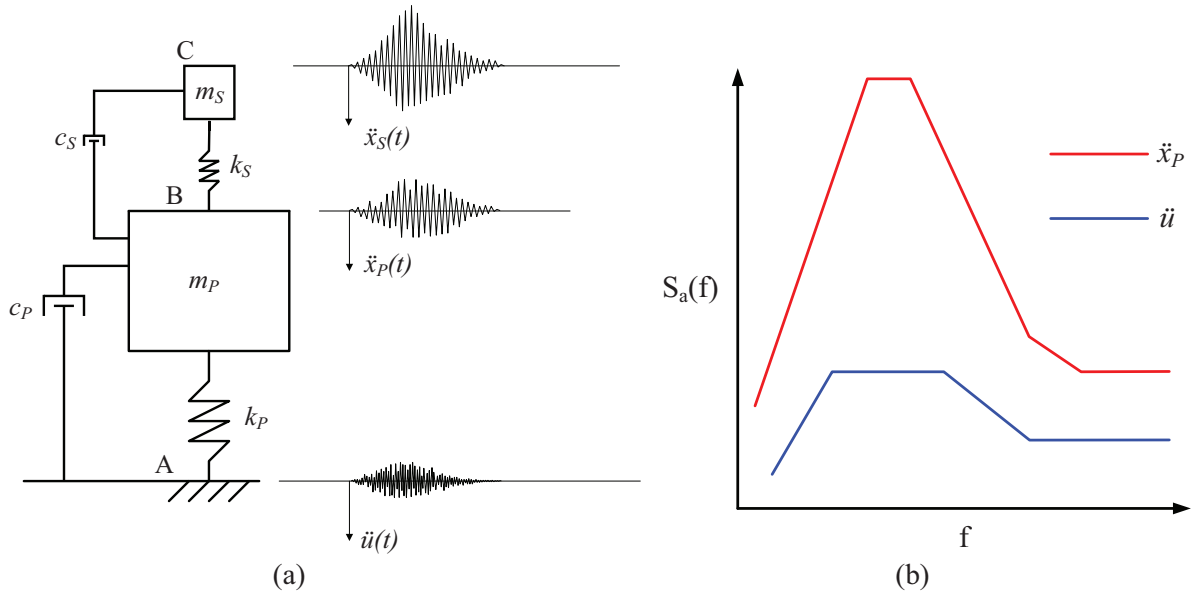


Figure 4. Two-Degree-of-Freedom System Model: (a) Schematic View of Model and Representative Acceleration Time Histories at Points A, B and C, and (b) Comparison of Base Motion Spectral Acceleration with Primary System Response Spectral Acceleration.

For the decoupled system, the primary system acceleration response spectra (response spectrum defining base motions for systems mounted at Pt. A in Fig. 4) are defined by:

$$S_a^u(\beta_P, \omega) = \max_t |\ddot{x}_P(\omega, t)| = \max_t \left| \omega^2 \int_0^t e^{-\beta_P \omega (t-\tau)} \sin[\omega(t-\tau)] \ddot{u}(\tau)\, d\tau \right| \quad (3)$$

And the secondary system acceleration response spectra (response spectrum defining base motions for systems mounted at Pt. B in Fig. 4) are defined by:

$$S_a^{x_P}(\beta_S, \omega) = \max_t |\ddot{x}_S(\omega, t)| = \max_t \left| \omega^2 \int_0^t e^{-\beta_S \omega (t-\tau)} \sin[\omega(t-\tau)] \ddot{x}_P(\tau)\, d\tau \right| \quad (4)$$

The primary system spectra, $S_a^u(\beta_p, \omega)$, of interest for this study, are selected to characterize the practical ranges of spectral bandwidths encountered for individual nuclear power plant required response spectra, from nearly pure harmonic or single frequency to bandwidths typical of nuclear power plant floor response spectra. With the assistance of the Q factor curves shown in Fig. 3, any of these single-peaked seismic response spectra can be approximated by sine beat motions. Sine beat motions are not capable of simulating the very broad-banded motions defined by design ground response spectra such as those from U.S. Nuclear Regulatory Commission Regulatory Guide 1.60 (1973). This does not detract from the utility of approaches developed in this study, since they are nearly always applied to ground motions which have been filtered.

Primary system spectra, $S_a^u(\beta_P, \omega)$, for β_p = 5%, and for sine beat motions, $\ddot{u}(t)$, with 2, 5 and 10 cycles per beat, are shown in Fig. 5. These spectral amplitudes and their time histories, along with the broadband spectra (from the seismic pulse) and its time history are all scaled, so that their peak accelerations are identical (Fig. 5). Fig. 5 is an analytical simulation of the enveloping process; 5% damped narrow-banded site specific response spectra (at some point in the structure, not on the ground) of various bandwidths are shown together with the enveloping uniform broad-banded spectrum. Since the primary system response

spectra are normalized with respect to the broad-banded input, the effect of different damping values is manifested in the shape of the narrow-banded spectra. Figure 6 shows the sine beat input time histories associated with the base input motion (at Pt. A) and the response of the primary system (at Pt. B), which serves as the input for the secondary system. Typical secondary system input time histories (at Pt. B) and typical secondary system response time histories (at Pt. C) for β_p = 5% are depicted in Fig. 7.

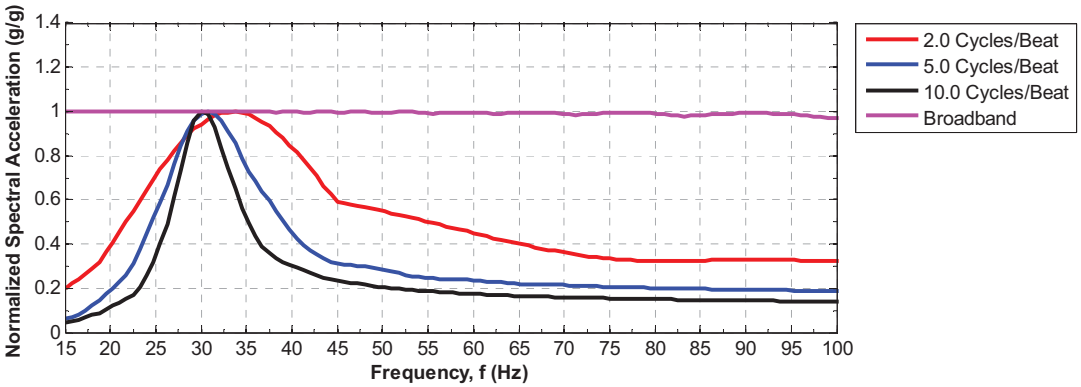


Figure 5. Response Spectra Input to Primary System for β_p = 5% (Pt. B Responses).

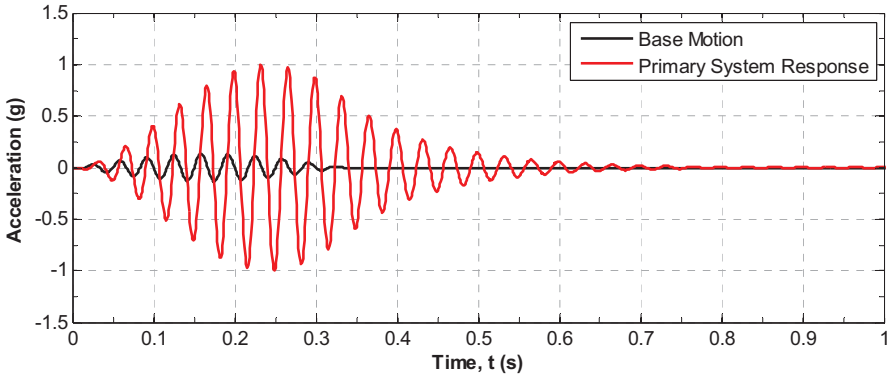


Figure 6. Base Motion Acceleration Time History, $\ddot{u}(t)$, for 10-Cycle per Beat Sine Beat at Pt. A and Primary System Response Acceleration Time History, $\ddot{x}_P(t)$, at Pt. B.

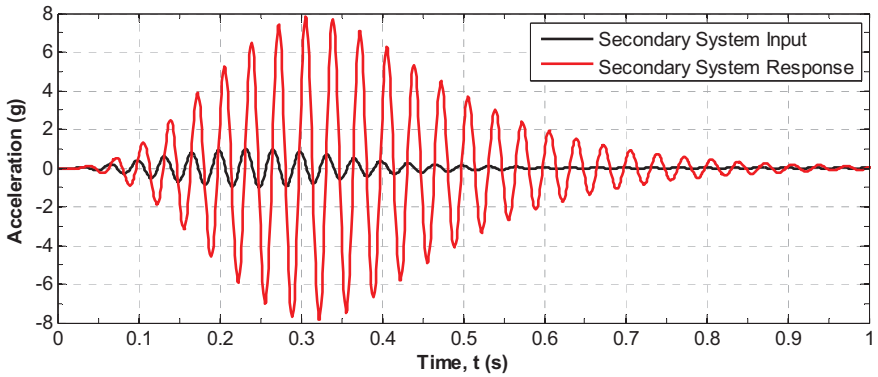


Figure 7. Secondary System Input Acceleration Time History, $\ddot{x}_P(t)$, at Pt. B and Secondary System Response Acceleration Time History, $\ddot{x}_S(t)$,at Pt. C for $\beta_p = \beta_s$ =5%.

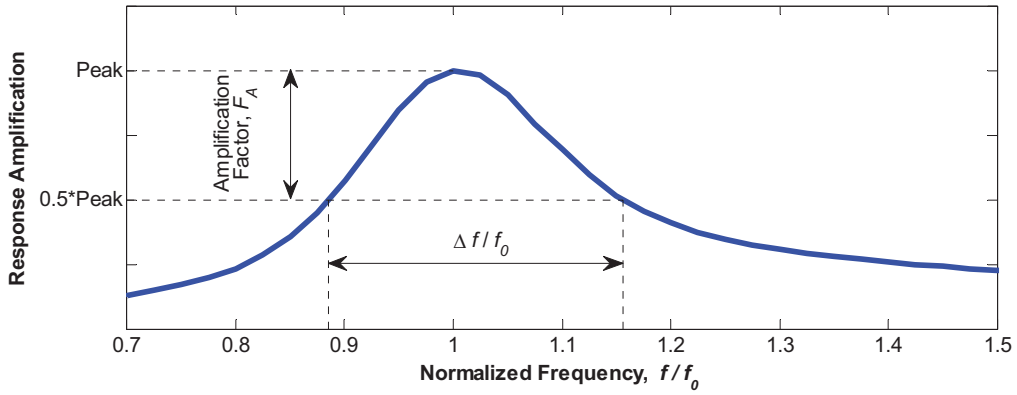


Figure 8. Half-Amplitude Bandwidth Characterization of Sine Beat Spectra.

RESULTS AND CONCLUSIONS

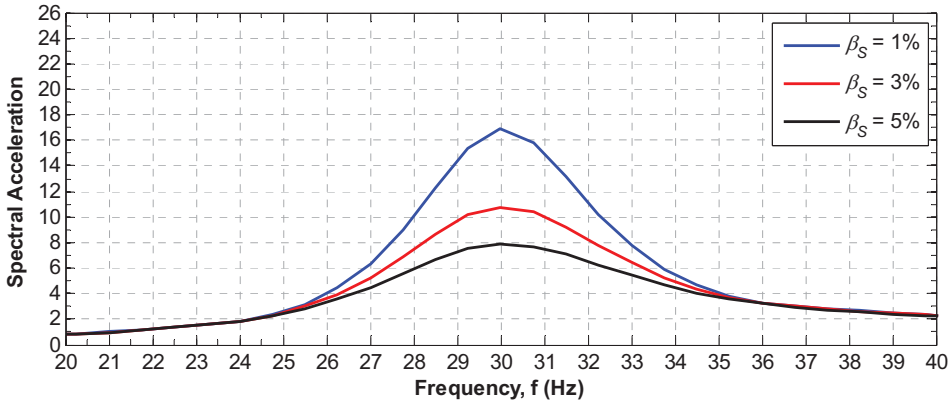
Figure 9 depicts the representative secondary system ISRS (response spectra at Pt. C) for various systems (different primary system and secondary system damping values; β_p, β_s) with the base input motion comprising of sine beats with 10 cycles per beat. These spectra confirm the anticipated near-resonance behaviours discussed earlier. Table 1 provides the amplification factors (at resonance), F_A, of the ISRS (secondary system response) acceleration for narrow-banded primary system input with respect to the ISRS acceleration for broad-banded primary system input. These factors depend on the "broad-bandedness" of the primary system input, which can be characterized by number of cycles per beat or by the half-amplitude bandwidth, $\Delta f/f_0$, defined in Fig. 8. Fig. 10 plots the amplification factors, F_A, as a function of number of cycles per beat, primary system damping, and secondary system damping. An approximate empirical representation of the amplification factors, F_A, determined from the plots and accurate to within 14%, is given by

$$F_A = \{[0.042 + 0.026(\beta_P - 1)](N - 2) + 1.882\}\left\{\frac{5-\beta_S}{4}[0.129 + 0.045(\beta_P - 1)] + 1\right\} \quad (5)$$

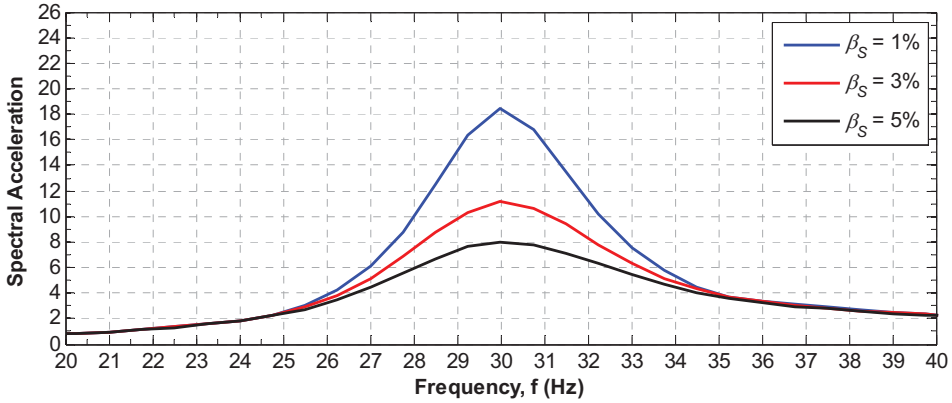
Broad-banded enveloping response spectra of individual composite spectra are, in general, not robust enough to capture the compound resonance effects of cascaded systems. More specifically:

1) For lightly damped primary and secondary systems, enveloping primary system narrow-banded seismic response spectra with composite broad-banded spectra results in under-amplified secondary system response spectra at resonance. Alternately stated, in-structure response spectra based on time histories compatible with composite enveloping spectra will underestimate in-structure spectral accelerations at resonance.

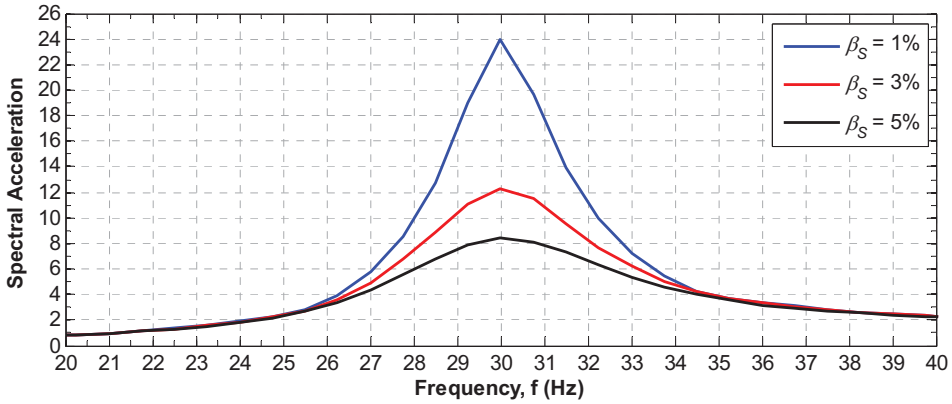
2) Amplification factors (F_A) are developed, which account for the underestimation of secondary system seismic response spectral accelerations at resonance by the broad-banded composite envelope (Table 1). It is evident that the factors depend on the primary and secondary system damping (β_p, β_s) and narrow-bandedness of the input motion, which can be represented either by the number of cycles per beat of the sine beat motions or the half-amplitude bandwidth of the response spectra (Fig. 8). These correlations are shown in Fig. 10.



(a) Primary System with β_P = 5%



(b) Primary System with β_P = 3%



(c) Primary System with β_P = 1%

Figure 9. Secondary System Response Spectra (Pt. C) for Various Systems (β_P, β_S) for Primary System Having a Base Motion Input Sine Beat of 10 Cycles per Beat.

Table 1: In-Structure Response Spectra Amplification Factors.

Primary System Sine Beat Input	$\beta_p = 5\%$			
	$\Delta f / f_0$	$\beta_s = 5\%$	$\beta_s = 3\%$	$\beta_s = 1\%$
2.0 Cyc/Beat	1.00	1.952	2.047	2.171
5.0 Cyc/Beat	0.47	2.488	2.651	2.871
10.0 Cyc/Beat	0.30	3.121	3.526	4.085
Primary System Sine Beat Input	$\beta_p = 3\%$			
	$\Delta f / f_0$	$\beta_s = 5\%$	$\beta_s = 3\%$	$\beta_s = 1\%$
2.0 Cyc/Beat	0.91	1.877	1.964	2.064
5.0 Cyc/Beat	0.44	2.254	2.390	2.548
10.0 Cyc/Beat	0.25	2.707	2.986	3.313
Primary System Sine Beat Input	$\beta_p = 1\%$			
	$\Delta f / f_0$	$\beta_s = 5\%$	$\beta_s = 3\%$	$\beta_s = 1\%$
2.0 Cyc/Beat	0.87	1.817	1.884	1.985
5.0 Cyc/Beat	0.38	1.978	2.065	2.176
10.0 Cyc/Beat	0.20	2.156	2.279	2.434

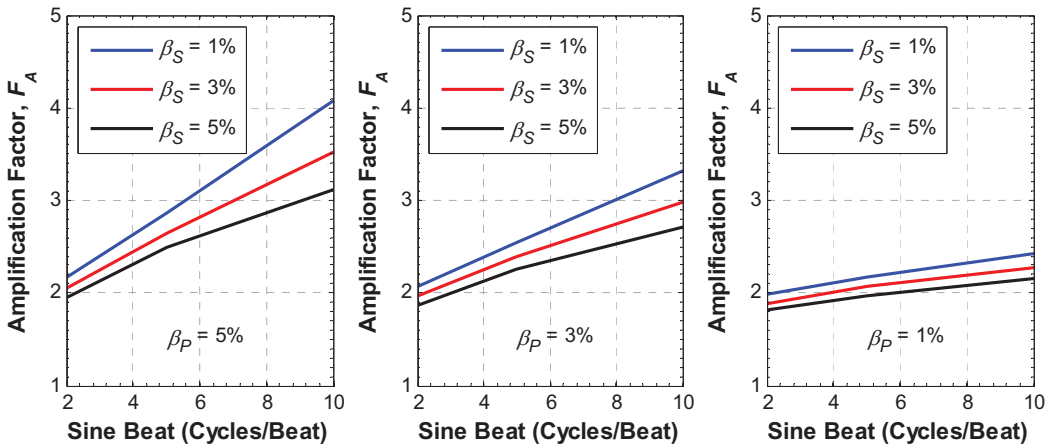


Figure 10. In-Structure Response Spectra Amplification Factors.

3) For response spectrum analyses (RSA), broadband composite envelopes will always yield more conservative structural responses than the individual enveloped spectra, since the modal responses are proportional to the spectral accelerations, and composite accelerations are greater than individual accelerations.

4) For testing (as opposed to in-structure response spectra generation) appropriate single frequency (sine beat) testing would eliminate the need for the considerations in this paper, provided that the test laboratory is given the applicable site spectrum along with the composite envelope.

5) Where the composite broad-banded spectrum is not flat, the amplification factors, F_A, can still be used. If the bounding spectrum is $S_a^{x_{P1}}(\beta_P, \omega)$ and the enveloped spectrum is $S_a^{x_{P2}}(\beta_P, \omega)$, the amplification factor, F_A, to be applied to the enveloping spectrum for qualification use is given by the ratio of F_A values for $S_a^{x_{S1}}(\beta_S, \omega)$ and $S_a^{x_{S2}}(\beta_S, \omega)$, since both F_A values are referenced to the same broadband secondary system input spectrum.

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