REPORT NO.
UCB/EERC-79/32
DECEMBER 1979

EARTHQUAKE ENGINEERING RESEARCH CENTER

ON RESPONSE OF STRUCTURES TO STATIONARY EXCITATION

by

ARMEN DER KIUREGHIAN

Report to Sponsor:
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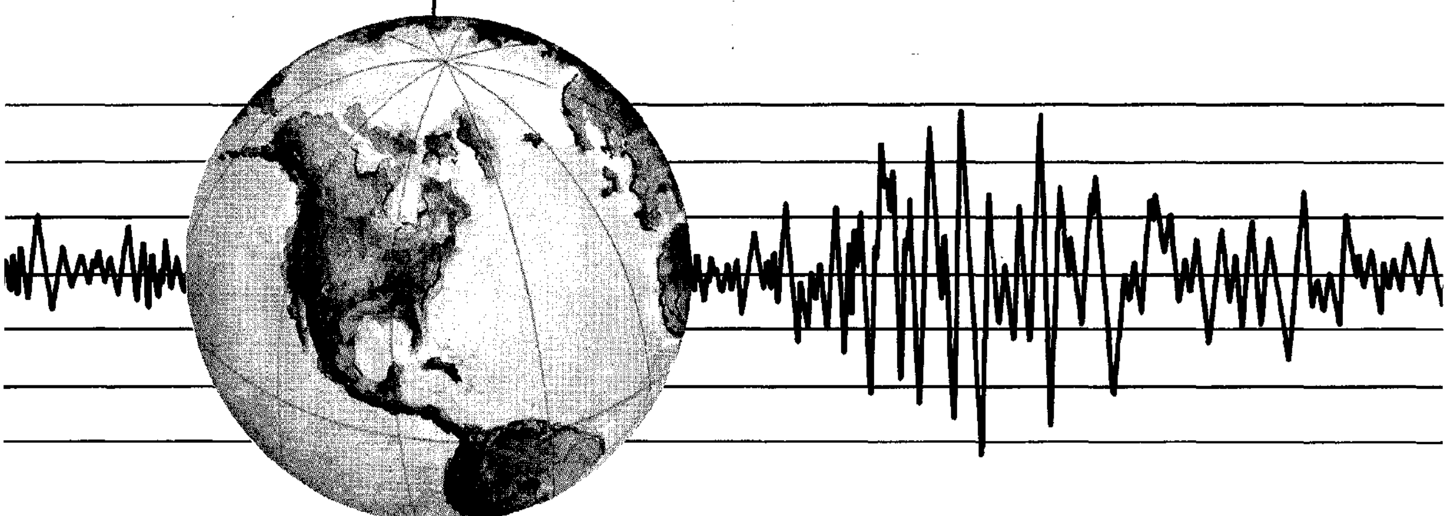

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BIBLIOGRAPHIC DATA SHEET	1. Report No. NSF/RA-790398	2.	3. Recipient's Accession No. PB80-166929

4. Title and Subtitle	5. Report Date
On Response of Structures To Stationary Excitation	December 1979
	6.
7. Author(s) Armen Der Kiureghian	8. Performing Organization Rept. No. UCB/EERC-79/32
9. Performing Organization Name and Address Earthquake Engineering Research Center University of California, Richmond Field Station 47th and Hoffman Blvd. Richmond, California 94804	10. Project/Task/Work Unit No. 11. Contract/Grant No. ENG-7905906
12. Sponsoring Organization Name and Address National Science Foundation 1800 G Street, N. W. Washington, D. C. 20550	13. Type of Report & Period Covered 14.

15. Supplementary Notes

16. Abstracts

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17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release Unlimited	UNCLASSIFIED	
	20. Security Class (This Page) UNCLASSIFIED	22. Price

ON RESPONSE OF STRUCTURES TO STATIONARY EXCITATION

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A report on research sponsored by
the National Science Foundation

Report No. UCB/EERC-79/32
Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley

December 1979

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ABSTRACT

Stationary responses of single- and multi-degree-of-freedom structures subjected to stationary input excitations are studied. Using a modal superposition procedure, closed form solutions for the first three spectral moments of response to white-noise and filtered white-noise inputs are derived. These solutions account for the correlation between modal responses of multi-degree structures; thus, they are applicable to structures with closely spaced modes. Special attention is given to excitations which are typical of earthquake ground motions. Various quantities of response can be obtained in terms of the three spectral moments. These include the mean squares of the response and its time derivative and, in the special case of Gaussian response, the mean zero-crossing rate and the mean, the variance, and the distribution of the peak response over a specified duration. In this regard, improved, semi-empirical relations for the mean and variance of the peak of a stationary Gaussian process are developed. Results from the study demonstrate the range of applicability of the white-noise model as an approximation for wide-band inputs.

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1. INTRODUCTION

The response of structural systems to stationary excitations is of wide engineering interest. Various quantities of response to such an excitation may be of interest in determining the reliability of an existing system or in making design decisions for a proposed one. Of particular interest among these are the probability distribution or the mean and variance of the peak response over a service duration of the system. Recently, Vanmarcke (8) has shown that many quantities of response to a stationary excitation can be expressed in terms of the first three moments of the response power spectral density. In particular, when the response is Gaussian, an expression for the distribution of the first-passage time is given by Vanmarcke (9) which can be used to evaluate the distribution of the peak in terms of the three spectral moments. No closed form solutions of the mean and variance for this distribution were given.

In the first part of this report, semi-empirical relations for the mean and variance of the peak of a stationary Gaussian process, consistent with Vanmarcke's distribution, are developed. In subsequent parts, closed form solutions for the spectral moments of the response of single- and multi-degree-of-freedom structures to the classes of white-noise and filtered white-noise input excitations are derived. For multi-degree systems, a modal superposition procedure is used which explicitly accounts for the correlation between modal responses. The method, thus, is applicable to structures with closely spaced modes. Throughout the analysis, results for response to filtered white noise are compared with those for response to white noise, thus demonstrating the range of applicability of the white-noise model as an approximation for wide-band inputs. In this study, particular attention is given to excitations which are typical of earthquake ground motions.

It is noted that some results reported herein are not new. However, the formulation presented here is unique and has definite practical advantages in application to structures with closely spaced modes.

2. PEAK OF STATIONARY GAUSSIAN PROCESS

Let $S(t)$ represent a stationary Gaussian process with zero mean. Let $G_S(\omega)$ denote its one-sided power spectral density. The maximum absolute value of the process over duration τ is defined as

$$S_\tau = \max_\tau |S(t)| \tag{1}$$

Based on Vanmarcke (9), the cumulative distribution of S_τ is

$$F_{S_\tau}(s) = \left(1 - e^{-\frac{a^2}{2}}\right) \exp\left(-\nu\tau e^{-\frac{a^2}{2}} \frac{1 - e^{-\sqrt{\frac{\pi}{2}} q_e a}}{1 - e^{-\frac{a^2}{2}}}\right), \quad s > 0 \tag{2}$$

in which $a = s/\sqrt{\lambda_0}$ is the normalized barrier level, $\nu = \sqrt{\lambda_2/\lambda_0}/\pi$ is the mean zero-crossing rate, $q_e = q^{1+b}$, and $q = \sqrt{1-\lambda_1^2/\lambda_0\lambda_2}$, where $b = 0.2$ is an empirically determined constant and

$$\lambda_m = \int_0^\infty \omega^m G_S(\omega)\, d\omega, \quad m = 0, 1, 2 \tag{3}$$

are moments of the power spectral density about the frequency origin. Note that $\lambda_0 = \sigma_S^2$ and $\lambda_2 = \sigma_{\dot{S}}^2$ are the mean squares of the process and its time derivative, respectively. The parameter q has a value between zero and one and is a measure of dispersion (spread) of $G_S(\omega)$ about its centroid. In deriving Eq. 2, Vanmarcke (9) has included the dependence between barrier crossings of the process through a consideration of their clumping effect. He has shown that q is inversely proportional to the number (clump size) of barrier crossings of the process which immediately follow each barrier crossing by its envelope. Thus, this parameter is a measure of dependence between barrier crossings. For narrow-band processes, q is small indicating a large clump size and, therefore, a significant dependence between crossings. For this reason, the commonly assumed Poisson model of crossings, which implies independence, produces poor results for such processes. Eq. 2 has been shown by Vanmarcke (9) to closely agree with simulation results obtained by Cook (2).

Using Eq. 2, the mean, μ_{S_τ}, and the standard deviation, σ_{S_τ}, of S_τ, as normalized with respect to σ_S, are evaluated and are shown in Fig. 1 for various values of q and for $\nu\tau = 1$ -

1000. (This is the range of values that is of interest in earthquake engineering.) Shown in Fig. 1 are also two other sets of curves. One set, the dashed curves, correspond to the asymptotic expressions of the mean and standard deviation given by Davenport (4) as

$$\mu_{S_\tau} = \left[\sqrt{2\ln\nu\tau} + \frac{0.5772}{\sqrt{2\ln\nu\tau}} \right] \sigma_S \tag{4}$$

$$\sigma_{S_\tau} = \left[\frac{\pi}{\sqrt{6}} \frac{1}{\sqrt{2\ln\nu\tau}} \right] \sigma_S \tag{5}$$

The other set, the solid thick curves, is based on a distribution of S_τ which assumes the Poisson model for the barrier crossings and considers a random initial condition, i.e.

$$F_{S_\tau}(s) = F_{|S(0)|}(s) \exp\left[-\nu\tau e^{-\frac{a^2}{2}} \right], \quad s > 0 \tag{6}$$

where $F_{|S(0)|}(s)$ is the cumulative distribution of $|S(0)|$ and is to assure that the process starts within the barriers s and $-s$. The asymptotic nature of Davenport's expressions, which are also based on the Poisson model of crossings, is apparent in Fig. 1 from a comparison of the two sets of curves. From this figure, the influence of the dependence between crossings on the mean and variance is found to be significant for small q. The distribution based on Poisson crossings generally tends to overestimate the mean and underestimate the variance. The error can be quite significant, i.e. more than 30 percent for q=0.11.

It appears in Fig. 1 that if the Poisson model of crossings is to be used, a reduced crossing rate, representing an equivalent rate of statistically independent crossings, would be appropriate. Let ν_e denote such a reduced mean zero-crossing rate. The ratio ν_e/ν as computed using Eq. 4 for the mean value is shown in Fig. 2. Observe that for narrow-band processes this ratio can be quite small, e.g. about 0.2 for $q = 0.11$. An empirical relation for ν_e in terms of ν and q is

$$\nu_e = \begin{cases} (1.63q^{0.45} - 0.38)\nu, & q < 0.69 \\ \nu, & q \geqslant 0.69 \end{cases} \tag{7}$$

This relation appears as dashed lines in Fig. 2. Using the reduced rate, the mean value for the distribution in Eq. 2 is

$$\mu_{S_\tau} = \left[\sqrt{2\ln\nu_e\tau} + \frac{0.5772}{\sqrt{2\ln\nu_e\tau}} \right] \sigma_S \tag{8}$$

For the standard deviation, whereas the same reduced rate gives good results when used with the exact curve based on Poisson crossings, unfortunately meaningless results are obtained with Eq. 5. An empirically determined expression that closely follows the standard deviation consistent with the distribution in Eq. 2 is

$$\sigma_{S_\tau} = \begin{cases} \left[\dfrac{1.2}{\sqrt{2\ln\nu_e\tau}} - \dfrac{5.4}{13+(2\ln\nu_e\tau)^{3.2}}\right]\sigma_S, & \nu_e\tau > 2.1 \\ 0.65\sigma_S, & \nu_e\tau \leqslant 2.1 \end{cases} \quad (9)$$

Eqs. 7-9 are applicable in the range $0.1 \leqslant q \leqslant 1$ and $5 \leqslant \nu\tau \leqslant 1000$. Resulting errors in the estimated values are generally within 3 percent for the mean and within 6 percent for the standard deviation.

The above discussion was restricted to zero-mean processes and to the maximum absolute value as defined in Eq. 1. With appropriate modification of parameters, however, same results also apply to other situations (see Refs. 6 and 9). For example, for the maximum positive value of a process with mean μ_S, it suffices to replace λ_0, ν, and q by $\lambda_0 - \mu_S^2$, $\nu/2$ and $2q$, respectively, and to add μ_S to the right-hand side of Eq. 8.

The remainder of this report concentrates on determining spectral moments for the stationary response of single- and multi-degree-of-freedom structures. With these moments determined, various response quantities such as the mean squares of the response and its time derivative and the parameters ν and q can be determined. In the case of Gaussian response, these quantities can be used to evaluate the distribution or the mean and variance of the peak response from the preceding relations. Other quantities, such as the mean crossing rate of a specified barrier level, may also be evaluated using well known relations in terms of spectral moments; see Ref. 8.

3. RESPONSE OF A SINGLE-DEGREE OSCILLATOR

Let $S(t)$ represent the displacement response of a single-degree, viscously damped, linear oscillator to a stationary excitation $F(t)$. With no loss of generality, let $F(t)$ be a zero-mean process. Neglecting the effect of initial conditions for a short-period oscillator, $S(t)$ is also stationary with zero mean. Its one-sided power spectral density is

$$G_S(\omega) = G_F(\omega)\,|H(\omega)|^2 \tag{10}$$

where $G_F(\omega)$ is the one-sided power spectral density of the excitation, and $H(\omega)$ is the complex frequency response function of the oscillator

$$H(\omega) = \frac{1}{\omega_0^2 - \omega^2 + 2i\zeta\omega_0\omega} \tag{11}$$

where ω_0 is the circular natural frequency and ζ is the damping ratio (6).

3.1 Response to White Noise (WN) -- For a white noise excitation, $G_F(\omega) = G_0$ is a constant. Using Eqs. 10 and 11 in Eq. 3, the spectral moments are obtained as

$$\lambda_0 = \frac{\pi G_0}{4\zeta\omega_0^3} \tag{12}$$

$$\lambda_1 = \frac{\pi G_0}{4\zeta\omega_0^2}\;\frac{1-\frac{2}{\pi}\tan^{-1}(\zeta/\sqrt{1-\zeta^2})}{\sqrt{1-\zeta^2}} \tag{13}$$

$$\lambda_2 = \frac{\pi G_0}{4\zeta\omega_0} \tag{14}$$

The results in Eqs. 12 and 14 are well known (6). The result in Eq. 13 is somewhat simpler than one given by Vanmarcke (8). From these,

$$\nu = \frac{\omega_0}{\pi} \tag{15}$$

$$q = \left[1 - \frac{1}{1-\zeta^2}\left\{1 - \frac{2}{\pi}\tan^{-1}\frac{\zeta}{\sqrt{1-\zeta^2}}\right\}^2\right]^{\frac{1}{2}} \tag{16}$$

are obtained. An empirically determined expression that closely follows the preceding relation is

$$q = (1.16\zeta^{0.15} - 0.21)^{2.2} \tag{17}$$

This equation has negligible error. Using Eq. 17 in Eq. 7, the reduced zero-crossing rate may be expressed in terms of the damping ratio as

$$\nu_e = \begin{cases} (1.90\zeta^{0.15} - 0.73)\nu, & \zeta < 0.54 \\ \nu, & \zeta \geqslant 0.54 \end{cases} \tag{18}$$

which is valid for $\zeta \geqslant 0.01$. In Fig. 1, damping coefficients corresponding to the various curves for response to white-noise input are shown in parenthesis. It is observed, thus, that in the case of response to white-noise input, the distribution as well as the mean and variance of the peak response can directly be obtained in terms of the frequency and the damping coefficient of the oscillator.

3.2 Response to Filtered White Noise (FWN) --Formally, filtered white noise results as the response of an oscillator to a white-noise input. It is often used to represent the input into a structure supported by a single-degree primary system which itself is subjected to a white-noise excitation. A common example is the base input into a structure situated on a soil layer which is excited by earthquake motions; see Ref. 1. More generally, however, the filtered white noise may be used as a convenient model for a large class of excitations. Consider a power spectral density of the form

$$G_F(\omega) = \frac{\omega_g^4 + 4\zeta_g^2\omega_g^2\omega^2}{(\omega_g^2-\omega^2)^2 + 4\zeta_g^2\omega_g^2\omega^2} G_0 \tag{19}$$

where ω_g and ζ_g are constants. This represents the power spectral density of the absolute acceleration response of a single-degree-of-freedom system to a white-noise base acceleration, where ω_g and ζ_g are the circular natural frequency and the damping coefficient, respectively. For example, Kanai (5) and Tajimi (7) have suggested $\omega_g = 5\pi$ and $\zeta_g = 0.6$ for modeling ground acceleration response during earthquakes. However, by proper selection of ω_g and ζ_g, Eq. 19 may be used to represent excitations with varying power spectral density shapes.

Spectral moments for response to filtered white noise are obtained by using Eqs. 10, 11, and 19 in Eq. 3. Here, the following results were obtained from more general solutions given in Appendix I:

$$\lambda_0 = \frac{\pi G_0}{4\zeta\omega_0^3}\frac{A}{F} + \frac{\pi G_0}{4\zeta_g\omega_g^3}\frac{B}{F} \tag{20}$$

$$\lambda_1 = \frac{\pi G_0}{4\zeta\omega_0^2}\frac{1-\frac{2}{\pi}\tan^{-1}(\zeta/\sqrt{1-\zeta^2})}{\sqrt{1-\zeta^2}}\frac{A'}{F}$$

$$+ \frac{\pi G_0}{4\zeta_g\omega_g^2}\frac{1-\frac{2}{\pi}\tan^{-1}(\zeta_g/\sqrt{1-\zeta_g^2})}{\sqrt{1-\zeta_g^2}}\frac{C}{F} - \frac{2G_0}{\omega_g^2}\frac{D}{F}\ln r \tag{21}$$

$$\lambda_2 = \frac{\pi G_0}{4\zeta\omega_0}\,\frac{A''}{F} + \frac{\pi G_0}{4\zeta_g\omega_g}\,\frac{E}{F} \tag{22}$$

where $r = \omega_0/\omega_g$ and

$$A = A_0 + 4\zeta^2 r^2[2 - 4\zeta_g^2 - (3-4\zeta^2)r^2 - 4\zeta_g^2 r^4]$$

$$A' = A_0 + 4\zeta^2 r^2[1 - 4\zeta_g^2 - 2(1-\zeta^2)r^2 - 2\zeta_g^2 r^4]$$

$$A'' = A_0 + 4\zeta^2 r^2[-4\zeta_g^2 - r^2]$$

$$B = 1 - 8\zeta_g^2 - 2(1-2\zeta^2)r^2 + (1+4\zeta_g^2)r^4$$

$$C = 1 - 4\zeta_g^2 - 2(1-2\zeta^2+2\zeta_g^2-4\zeta^2\zeta_g^2)r^2 + (1+4\zeta_g^2-8\zeta_g^4)r^4$$

$$D = 1 - (1-2\zeta^2)r^2 - 2\zeta_g^2 r^4$$

$$E = 1 - 2(1-2\zeta^2+4\zeta_g^2-8\zeta^2\zeta_g^2)r^2 + (1+4\zeta_g^2-16\zeta_g^4)r^4$$

$$F = F_0 + 8\zeta^2 r^2[1 - 2\zeta_g^2 - 2(1-\zeta^2)r^2 + (1-2\zeta_g^2)r^4]$$

in which

$$A_0 = 1 - 2(1-4\zeta_g^2)r^2 + (1+4\zeta_g^2)r^4$$

$$F_0 = 1 - 4(1-2\zeta_g^2)r^2 + 2(3-8\zeta_g^2+8\zeta_g^4)r^4 - 4(1-2\zeta_g^2)r^6 + r^8$$

Ratios of spectral moments from Eqs. 20-22 to their corresponding values for response to white noise, Eqs. 12-14, are plotted in Fig. 3 against r and for selected values of ζ_g. It is interesting to note that these ratios for the three moments are quite the same. Also note that even for wide-band excitations with ζ_g as large as 0.60, e.g. for earthquake type excitations, these ratios can considerably deviate from unity.

Several special cases in preceding relations are noteworthy. First, as $\omega_g \to \infty$, the filtered white noise approaches a white noise. In this case $r \to 0$, A, A', A'', and $F \to 1$, and terms in Eqs. 20-22 with ω_g in their denominators vanish. These expressions then reduce to Eqs. 12-14 for response to white-noise input. Second, for $\zeta << \zeta_g$, e.g. for a lightly damped oscillator and a wide-band input, first terms on the right-hand sides of Eqs. 20-22 are dominant, provided ω_0 is not much greater than ω_g. (Note that for $\omega_0 >> \omega_g$, the oscillator frequency is beyond significant frequencies of the excitation. Therefore, such a case is of less interest.) Observe that in this case $A \approx A' \approx A'' \approx A_0$ and $F \approx F_0$. Thus, the spectral moments in this case differ from those for response to white noise by the factor A_0/F_0. This factor, which is only a function of r and ζ_g, is compared in Fig. 3 with the exact results. Observe in this figure that this factor closely agrees with the exact ratios of spectral moments over the significant range of frequencies when ζ/ζ_g is small; say, when it is of order 0.1. Next, consider the case where ζ and $\zeta_g << 1$, e.g. a lightly damped oscillator and a narrow-band excitation. Under the condition that r is not in the neighborhood of 1, Eqs. 20-22 can be approximated by

$$\lambda_m \approx \omega_0^m A_H G_F(\omega_0) + \omega_g^m A_F |H(\omega_g)|^2, \quad m = 0,1,2 \tag{23}$$

where $A_H = \pi/4\zeta\omega_0^3$ and $A_F = \pi G_0 \omega_g / 4\zeta_g$ are areas under $|H(\omega)|^2$ and $G_F(\omega)$ diagrams, respectively. This simple relation can be used, for example, to approximate the response of a secondary system supported by a lightly damped primary system whose natural frequencies are well separated. Finally, in the case of resonance, when $\omega_0 = \omega_g$ and $r = 1$, Eqs. 20-22 reduce to

$$\lambda_0 = \frac{\pi G_0}{4\zeta\omega_0^3} \frac{1+4\zeta_g(\zeta_g+\zeta)}{4\zeta_g(\zeta_g+\zeta)} \tag{24}$$

$$\lambda_1 = \frac{\pi G_0}{4\zeta\omega_0^2}\left[\frac{1-\frac{2}{\pi}\tan^{-1}(\zeta/\sqrt{1-\zeta^2})}{\sqrt{1-\zeta^2}} \frac{1+4\zeta_g^2-2\zeta^2}{4(\zeta_g^2-\zeta^2)} - \frac{1-\frac{2}{\pi}\tan^{-1}(\zeta_g/\sqrt{1-\zeta_g^2})}{\sqrt{1-\zeta_g^2}} \frac{\zeta(1+2\zeta_g^2)}{4\zeta_g(\zeta_g^2-\zeta^2)}\right] \tag{25}$$

$$\lambda_2 = \frac{\pi G_0}{4\zeta\omega_0} \frac{1+4\zeta_g^2}{4\zeta_g(\zeta_g+\zeta)} \tag{26}$$

It is observed that in this case the spectral moments for response to filtered white noise are equal to those for response to white noise as amplified by a factor in terms of ζ_g and ζ. Note that the amplification factor can be very large for small ζ_g, i.e. for narrow-band inputs, thus indicating the inadequacy of the white-noise model for such excitations.

Attention is now focused on parameters $\nu = \sqrt{\lambda_2/\lambda_0}/\pi$ and $q = \sqrt{1-\lambda_1^2/\lambda_0\lambda_2}$. Using Eqs. 20-22, ratios of these parameters to their corresponding values for response to white noise, Eqs. 15 and 16, are plotted in Fig. 4 against r for selected values of ζ_g. Several observations in this figure are noteworthy. First observe that at $r = 1$, the mean zero-crossing rate for response to filtered white noise, denoted by ν_{FWN}, is virtually equal to that for response to white-noise,

ν_{WN}. This result is also predictable from Eqs. 24 and 26. Second, observe that in general for $r<1, \nu_{FWN} \geqslant \nu_{WN}$ and for $r>1$, $\nu_{FWN} < \nu_{WN}$. This result is more pronounced for heavily damped oscillators and for narrow-band inputs. Finally, note that for $\zeta << \zeta_g$ and for not too large r, ν_{FWN} is nearly equal to ν_{WN}. This result is also predictable from Eqs. 20 and 22, where first terms on the right-hand sides become dominant and $A/F \approx A''/F \approx A_0/F_0$.

For the parameter q, an interesting behavior is observed at $r=1$. At this point, q_{FWN} is much smaller than q_{WN}, especially for small ζ_g, i.e. for a narrow-band input. This results because the power spectral density of response in this case is sharply centered around the resonance frequency and, therefore, has a small dispersion. Note that a significant reduction in q may result from this phenomenon. At $r<1$, q_{FWN} is generally close to q_{WN} for large ζ_g, i.e. for wide-band inputs. However, at large values of r , the response power spectral density becomes bimodal and, as a result, q_{FWN} becomes larger than q_{WN} indicating a wider dispersion in the frequency distribution.

4. RESPONSE OF MULTI-DEGREE SYSTEMS

Consider an n-degree-of-freedom, viscously damped, linear system having classical modes. Let ω_i, ζ_i, $i=1,2,...,n$, represent its natural circular frequencies and damping coefficients, respectively. It is well known (e.g., see Ref.1) that any response of such a system can be expressed in terms of modal contributions as

$$R(t) = \sum_i R_i(t) = \sum_i \Psi_i S_i(t) \tag{27}$$

where $R_i(t) = \Psi_i S_i(t)$ is the contribution from mode i, in which Ψ_i is the effective participation factor, a constant in terms of modal vectors and the mass matrix, and $S_i(t)$ is the i-th normal coordinate representing the response of an oscillator of frequency ω_i and damping ratio ζ_i to the given input excitation. For a zero-mean stationary input $F(t)$, neglecting the effect of initial conditions for short period systems, $S_i(t)$ and, hence, $R(t)$ are also stationary with zero means. The power spectral density of response is

$$G_R(\omega) = \sum_i \sum_j \Psi_i \Psi_j G_F(\omega) H_i(\omega) H_j^*(\omega) \tag{28}$$

where $H_i(\omega)$ is as in Eq. 11 with ω_0 and ζ replaced by ω_i and ζ_i, respectively, and the asterisk denotes a complex conjugate. Note that since terms corresponding to indices *i,j* and *j,i* in the summation are complex conjugates, $G_R(\omega)$ is always real valued. In evaluating a typical term, therefore, only the real part will be considered.

Using Eq. 28 in Eq. 3, the spectral moments of the response are

$$\lambda_m = \int_0^\infty \omega^m G_R(\omega) d\omega = \sum_i \sum_j \Psi_i \Psi_j \lambda_{m,ij}, \quad m = 0, 1, 2 \tag{29}$$

where

$$\lambda_{m,ij} = \mathrm{Re}\left[\int_0^\infty \omega^m G_F(\omega) H_i(\omega) H_j^*(\omega) d\omega\right], \quad m = 0, 1, 2 \tag{30}$$

may be defined as cross-spectral moments of normal coordinates $S_i(t)$ and $S_j(t)$, associated with modes i and j. It can be shown that $\lambda_{0,ij}$ and $\lambda_{2,ij}$ are covariances between the normal coordinates, $S_i(t)$ and $S_j(t)$, and between their time derivatives, $\dot{S}_i(t)$ and $\dot{S}_j(t)$, respectively.

It is useful to introduce coefficients

$$\rho_{m,ij} = \frac{\lambda_{m,ij}}{\sqrt{\lambda_{m,ii}\lambda_{m,jj}}}, \quad m = 0, 1, 2 \tag{31}$$

Note that $\rho_{0,ij}$ and $\rho_{2,ij}$ represent correlation coefficients between $S_i(t)$ and $S_j(t)$ and between $\dot{S}_i(t)$ and $\dot{S}_j(t)$, respectively. Although $\rho_{1,ij}$ has no physical interpretation, it is expected to also behave like a correlation coefficient. Using Eq. 31 in Eq. 29, the spectral moments of response can be expressed in terms of unimodal moments as

$$\lambda_m = \sum_i \sum_j \Psi_i \Psi_j \rho_{m,ij} \sqrt{\lambda_{m,ii}\lambda_{m,jj}}, \quad m=0, 1, 2 \tag{32}$$

where $\lambda_{m,ii}$ represent spectral moments of the response of a single-degree oscillator of frequency ω_i and damping coefficient ζ_i to the specified input, as given in the preceding section. In the following, solutions of cross-spectral moments, $\lambda_{m,ij}$, and coefficients $\rho_{m,ij}$ for responses to the two classes of excitations under consideration are presented.

4.1 Response to White Noise -- For a white-noise input, using the residue theorem of integration for $\lambda_{0,ij}$ and $\lambda_{2,ij}$, and the method of partial fractions for $\lambda_{1,ij}$, the following results are obtained:

$$\lambda_{0,ij} = \frac{2\pi G_0}{K_{ij}} (\zeta_i\omega_i + \zeta_j\omega_j) \tag{33}$$

$$\lambda_{1,ij} = \frac{2\pi G_0}{K_{ij}} \left\{ \frac{1 - \frac{2}{\pi}\tan^{-1}(\zeta_i/\sqrt{1-\zeta_i^2})}{4\sqrt{1-\zeta_i^2}} [\omega_i(\zeta_i\omega_i + \zeta_j\omega_j) + \omega_j(\zeta_i\omega_j + \zeta_j\omega_i)] \right.$$
$$+ \frac{1 - \frac{2}{\pi}\tan^{-1}(\zeta_j/\sqrt{1-\zeta_j^2})}{4\sqrt{1-\zeta_j^2}} [\omega_i(\zeta_i\omega_j + \zeta_j\omega_i) + \omega_j(\zeta_i\omega_i + \zeta_j\omega_j)]$$
$$\left. - \frac{\ln\frac{\omega_i}{\omega_j}}{2\pi} (\omega_i^2 - \omega_j^2) \right\} \tag{34}$$

$$\lambda_{2,ij} = \frac{2\pi G_0}{K_{ij}} (\zeta_i\omega_j + \zeta_j\omega_i)\omega_i\omega_j \tag{35}$$

where

$$K_{ij} = (\omega_i^2 - \omega_j^2)^2 + 4\zeta_i\zeta_j\omega_i\omega_j(\omega_i^2 + \omega_j^2) + 4(\zeta_i^2 + \zeta_j^2)\omega_i^2\omega_j^2 \tag{36}$$

Note that for $i=j$, Eqs. 33-35 reduce to Eqs. 12-14 for a single-degree oscillator. Using Eqs. 33 and 35 together with Eqs. 12 and 14 in Eq. 31, correlation coefficients $\rho_{0,ij}$ and $\rho_{2,ij}$ are obtained as

$$\rho_{0,ij} = \frac{8\sqrt{\zeta_i\zeta_j\omega_i\omega_j}(\zeta_i\omega_i + \zeta_j\omega_j)\omega_i\omega_j}{K_{ij}} \tag{37}$$

$$\rho_{2,ij} = \frac{8\sqrt{\zeta_i\zeta_j\omega_i\omega_j}(\zeta_i\omega_j + \zeta_j\omega_i)\omega_i\omega_j}{K_{ij}} \tag{38}$$

The corresponding derivation for $\rho_{1,ij}$ does not yield a simple expression and for that reason is not presented here.

The coefficients $\rho_{m,ij}$ for response to white-noise input are shown in Fig. 5 as plotted against the ratio ω_i/ω_j for various damping values. Observe that all three ratios rapidly diminish as the two frequencies depart, particularly at small damping . Thus, cross-modal terms in Eqs. 29 or 32 are only significant for modes with closely spaced frequencies. As a simple rule, these terms can be dropped when ω_i/ω_j is less than $0.2/(\zeta_i + \zeta_j + 0.2)$, which approximately corresponds to $\rho_{m,ij}$ less than 0.1.

For small damping and for closely spaced modes, Eqs. 37 and 38 as well as the corresponding relation for $\rho_{1,ij}$ can be reduced, through a first-order approximation, to

$$\rho_{0,ij} \approx \frac{2\sqrt{\zeta_i \zeta_j}\left[(\omega_i+\omega_j)^2(\zeta_i+\zeta_j) + (\omega_i^2-\omega_j^2)(\zeta_i-\zeta_j)\right]}{4(\omega_i-\omega_j)^2 + (\zeta_i+\zeta_j)^2(\omega_i+\omega_j)^2} \tag{39}$$

$$\rho_{1,ij} \approx \frac{2\sqrt{\zeta_i \zeta_j}\left[(\omega_i+\omega_j)^2(\zeta_i+\zeta_j) - \frac{4}{\pi}(\omega_i-\omega_j)^2\right]}{4(\omega_i-\omega_j)^2 + (\zeta_i+\zeta_j)^2(\omega_i+\omega_j)^2} \tag{40}$$

$$\rho_{2,ij} \approx \frac{2\sqrt{\zeta_i \zeta_j}\left[(\omega_i+\omega_j)^2(\zeta_i+\zeta_j) - (\omega_i^2-\omega_j^2)(\zeta_i-\zeta_j)\right]}{4(\omega_i-\omega_j)^2 + (\zeta_i+\zeta_j)^2(\omega_i+\omega_j)^2} \tag{41}$$

These expressions are compared in Fig. 5 with exact results. Observe that these approximate expressions provide reasonable accuracy for damping values as large as 0.20, and that they should be adequate for most practical applications.

4.2 Response to Filtered White Noise --Solutions of cross-spectral moments for response to filtered white-noise input are summarized in Appendix I. These are rather long expressions of modal frequencies, damping ratios, and the filter parameters, ω_g and ζ_g. Although approximate expressions for small damping are possible, such results are not expected to be simple enough to justify their use in place of the exact expressions. One possible simplification, however, is to use the approximate expressions of $\rho_{m,ij}$ in Eqs. 39-41, which were based on a white-noise input, in this case when ζ_g is large, i.e. when the excitation is wide-band. For $\zeta_g = 0.6$, i.e. for earthquake type excitations, comparisons between approximate expressions in Eqs. 39-41 and exact values of these coefficients from Appendix I, are shown in Fig. 6. Note that the approximate expressions are reasonably accurate, particularly for small damping and for values of the modal frequencies that are within the dominant frequencies of the input excitation. When this approximation is possible, Eq. 32 may be used to evaluate the spectral moments of response, where $\lambda_{m,ii}$ and $\lambda_{m,jj}$ are now obtained from Eqs. 20-22.

5. SUMMARY AND CONCLUSIONS

The responses of single- and multi-degree-of-freedom structures to stationary input excitations are studied. Closed form solutions for the first three moments of the power spectral density of response to the classes of white-noise and filtered white-noise inputs are presented. Typically, these are expressed in terms of cross-spectral moments between normal coordinates, which are functions of the corresponding modal frequencies and damping coefficients and of the parameters of the input power spectral density. These terms signify the correlation between modal responses of multi-degree-of-freedom structures. Results for a single oscillator can be derived as a specialization of cross-modal terms. For response to wide-band inputs, it is demonstrated that cross-terms between modal responses are only significant for modes with closely spaced frequencies and can be neglected otherwise.

Various statistical quantities of the response can be obtained in terms of the spectral moments. These include the mean square values of the response and its time derivative and, in the special case of Gaussian response, mean rates of barrier crossings and the mean, the variance, and the distribution of the peak response over a specified duration. In this regard, improved semi-empirical relations for the mean and variance of the peak of a stationary Gaussian process are developed. Finally, through comparisons of results for the two classes of input excitations, the range of applicability of the white-noise model as an approximation for wide-band inputs is demonstrated.

6. ACKNOWLEDGEMENT

The writer wishes to thank J. Sackman for many enlightening discussions and M. Moghtaderizadeh for assistance in the computer work. This work was supported by the National Science Foundation under Grant No. ENG-7905906. The support is gratefully acknowledged.

APPENDIX I. - CROSS-SPECTRAL MOMENTS FOR RESPONSE TO FWN INPUT

The following results were derived using the residue theorem for $\lambda_{0,ij}$ and $\lambda_{2,ij}$, and the method of partial fractions for $\lambda_{1,ij}$. The results for a single oscillator, Eqs. 20-22, are obtained by letting $\omega_i = \omega_j = \omega_0$ and $\zeta_i = \zeta_j = \zeta$.

Let $a_0 = \zeta_g\omega_g$, $a_1 = \zeta_i\omega_i$, $a_2 = \zeta_j\omega_j$, $b_0 = \omega_g\sqrt{1-\zeta_g^2}$, $b_1 = \omega_i\sqrt{1-\zeta_i^2}$, and $b_2 = \omega_j\sqrt{1-\zeta_j^2}$. Also let $X_k = \omega_g^2 + 4\zeta_g^2(b_k^2 - a_k^2)$, $Y_k = 8\zeta_g^2 a_k b_k$, $k = 0, 1, 2$, and define functionals:

$$A_1 = A_1(a_0, b_0, a_1, b_1, a_2, b_2)$$
$$= \left[(a_0-a_1)^2 - (b_0^2-b_1^2)\right]\left[(a_0+a_2)^2 - (b_0^2-b_2^2)\right] - 4b_0^2(a_0-a_1)(a_0+a_2)$$
$$A_2 = A_2(a_0, b_0, a_1, b_1, a_2, b_2)$$
$$= 2b_0(a_0+a_2)\left[(a_0-a_1)^2 - (b_0^2-b_1^2)\right] + 2b_0(a_0-a_1)\left[(a_0+a_2)^2 - (b_0^2-b_2^2)\right]$$
$$A_3 = A_1(a_1, b_1, -a_0, b_0, a_2, b_2),\ A_4 = A_2(a_1, b_1, -a_0, b_0, a_2, b_2),$$
$$A_5 = A_1(a_0, b_0, -a_1, b_1, -a_2, b_2),\ A_6 = A_2(a_0, b_0, -a_1, b_1, -a_2, b_2),$$
$$A_7 = A_1(a_1, b_1, a_0, b_0, a_0, b_0),\ A_8 = A_2(a_1, b_1, a_0, b_0, a_0, b_0),$$
$$A_9 = A_1(a_2, b_2, a_0, b_0, a_0, b_0),\ A_{10} = A_2(a_2, b_2, a_0, b_0, a_0, b_0),$$
$$B_1 = B_1(a_0, b_0, a_1, b_1, a_2, b_2) = b_1\left[(a_1+a_2)^2 - (b_1^2-b_2^2)\right] - 2a_1b_1(a_1+a_2),$$
$$B_2 = B_2(a_0, b_0, a_1, b_1, a_2, b_2) = a_1\left[(a_1+a_2)^2 - (b_1^2-b_2^2)\right] + 2b_1^2(a_1+a_2),$$
$$B_3 = B_1(a_0, b_0, a_2, b_2, a_1, b_1),\ B_4 = B_2(a_0, b_0, a_2, b_2, a_1, b_1),$$
$$C_1 = \left[(a_0-a_1)^2 + (b_0^2-b_1^2)\right]X_1 + 2b_1(a_0-a_1)Y_1,$$
$$C_2 = 2b_1(a_0-a_1)X_1 - \left[(a_0-a_1)^2 + (b_0^2-b_1^2)\right]Y_1,$$
$$D_1 = D_1(a_0, b_0, a_1, b_1, a_2, b_2) = \left\{\left[(a_0-a_1)^2 - (b_0^2-b_1^2)\right]^2 + 4b_0^2(a_0-a_1)^2\right\}$$
$$\times\left\{\left[(a_0+a_2)^2 - (b_0^2-b_2^2)\right]^2 + 4b_0^2(a_0+a_2)^2\right\},$$
$$D_2 = D_2(a_0, b_0, a_1, b_1, a_2, b_2) = \left\{\left[(a_0-a_1)^2 + (b_0^2-b_1^2)\right]^2 + 4b_1^2(a_0-a_1)^2\right\}$$
$$\times\left\{\left[(a_0+a_1)^2 + (b_0^2-b_1^2)\right]^2 + 4b_1^2(a_0+a_1)^2\right\}\left\{\left[(a_1+a_2)^2 - (b_1^2-b_2^2)\right]^2 + 4b_1^2(a_1+a_2)^2\right\}$$
$$D_3 = D_1(a_0, b_0, -a_1, b_1, -a_2, b_2),\ \text{and}\ D_4 = D_2(a_0, b_0, a_2, b_2, a_1, b_1)$$

The solutions for cross-spectral moments, Eqs. 30, then are

$$\lambda_{0,ij} = \pi G_0\omega_g^2\left[\frac{(b_0X_0 + a_0Y_0)A_1 + (a_0X_0 - b_0Y_0)A_2}{4a_0b_0\omega_g^2 D_1} + \frac{C_1A_4 - C_2A_3}{b_1D_2}\right] \tag{42}$$

$$\lambda_{1,ij} = \pi G_0\omega_g^2\Bigg[\frac{(X_0A_1-Y_0A_2)D_3+(X_0A_5-Y_0A_6)D_1}{8a_0b_0D_1D_3}\left(1-\frac{2}{\pi}\tan^{-1}\frac{\zeta_g}{\sqrt{1-\zeta_g^2}}\right)$$
$$+\frac{(X_1B_2+Y_1B_1)A_7+(X_1B_1-Y_1B_2)A_8}{2b_1D_2}\left(1-\frac{2}{\pi}\tan^{-1}\frac{\zeta_i}{\sqrt{1-\zeta_i^2}}\right)$$
$$+\frac{(X_2B_4+Y_2B_3)A_9+(X_2B_3-Y_2B_4)A_{10}}{2b_2D_4}\left(1-\frac{2}{\pi}\tan^{-1}\frac{\zeta_j}{\sqrt{1-\zeta_j^2}}\right)$$
$$-\frac{(X_0A_2+Y_0A_1)D_3+(X_0A_6+Y_0A_5)D_1}{4\pi a_0b_0D_1D_3}\ln\omega_g$$
$$+\frac{(X_1B_1-Y_1B_2)A_7-(X_1B_2+Y_1B_1)A_8}{\pi b_1D_2}\ln\omega_i$$
$$+\frac{(X_2B_3-Y_2B_4)A_9-(X_2B_4+Y_2B_3)A_{10}}{\pi b_2D_4}\ln\omega_j\Bigg] \tag{43}$$

and

$$\lambda_{2,ij} = \pi G_0\omega_g^2\Bigg\{\frac{(b_0X_0-a_0Y_0)A_1-(a_0X_0+b_0Y_0)A_2}{4a_0b_0D_1}$$
$$+\frac{C_1[2a_1b_1A_3-(a_1^2-b_1^2)A_4]+C_2[2a_1b_1A_4+(a_1^2-b_1^2)A_3]}{b_1D_2}\Bigg\} \tag{44}$$

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APPENDIX III - NOTATION

The following symbols are used in this paper:

$a = s/\sigma_S$ = normalized barrier level;
a_0, b_0 = functions of ω_g and ζ_g;
a_1, b_1 = functions of ω_i and ζ_i;
a_2, b_2 = functions of ω_j and ζ_j;
A, A', A'', B, C, D, E, F = functions of ζ, ζ_g, and r;
A_0, F_0 = functions of ζ_g and r;
A_k, B_k, C_k, D_k = functions of ω_g, ζ_g, ω_i, ζ_i, ω_j, and ζ_j;
A_F, A_H = areas under $G_F(\omega)$ and $|H(\omega)|^2$ diagrams, respectively;
b = an empirically determined constant;
$F(t)$ = stationary Gaussian excitation;
$F_{S_\tau}(s)$ = cumulative probability distribution of S_τ ;
G_0 = power spectral density scale factor;
$G_F(\omega)$, $G_S(\omega)$ = power spectral densities of $F(t)$ and $S(t)$, respectively;
$H(\omega)$ = frequency response function of an oscillator;
$H_i(\omega)$ = frequency response function of mode i;
K_{ij} = a function of ω_i, ζ_i, ω_j, and ζ_j;
q, q_e = coefficients related to the shape of power spectral density;
r = ω_0/ω_g;
$R(t)$ = response of multi-degree-of-freedom system;
$\dot{R}(t)$, $\dot{S}(t)$ = time derivatives of $R(t)$ and $S(t)$, respectively;
$S(t)$ = response of single-degree-of-freedom system;
$S_i(t)$ = i-th normal coordinate;
S_τ = maximum absolute value of $S(t)$ over τ;
X_0, Y_0 = functions of ω_g and ζ_g;
X_1, Y_1 = functions of ω_g, ζ_g, ω_i, and ζ_i;
X_2, Y_2 = functions of ω_g, ζ_g, ω_j, and ζ_j;
λ_0, λ_1, λ_2 = spectral moments;
$\lambda_{0,ij}$, $\lambda_{1,ij}$, $\lambda_{2,ij}$ = cross-spectral moments;
μ = mean value;
ν = mean zero-crossing rate;
ν_e = reduced mean zero-crossing rate;
$\rho_{0,ij}$, $\rho_{1,ij}$, $\rho_{2,ij}$ = coefficients associated with $\lambda_{0,ij}$, $\lambda_{1,ij}$, and $\lambda_{2,ij}$, respectively;
σ = standard deviation;
τ = duration of excitation;
Ψ_i = effective participation factor of mode i;
ω_0, ζ = natural circular frequency and damping ratio of an oscillator, respectively;

ω_i, ζ_i = natural circular frequency and damping ratio of mode i ; and

ω_g, ζ_g = parameters describing the power spectral density of filtered white noise.

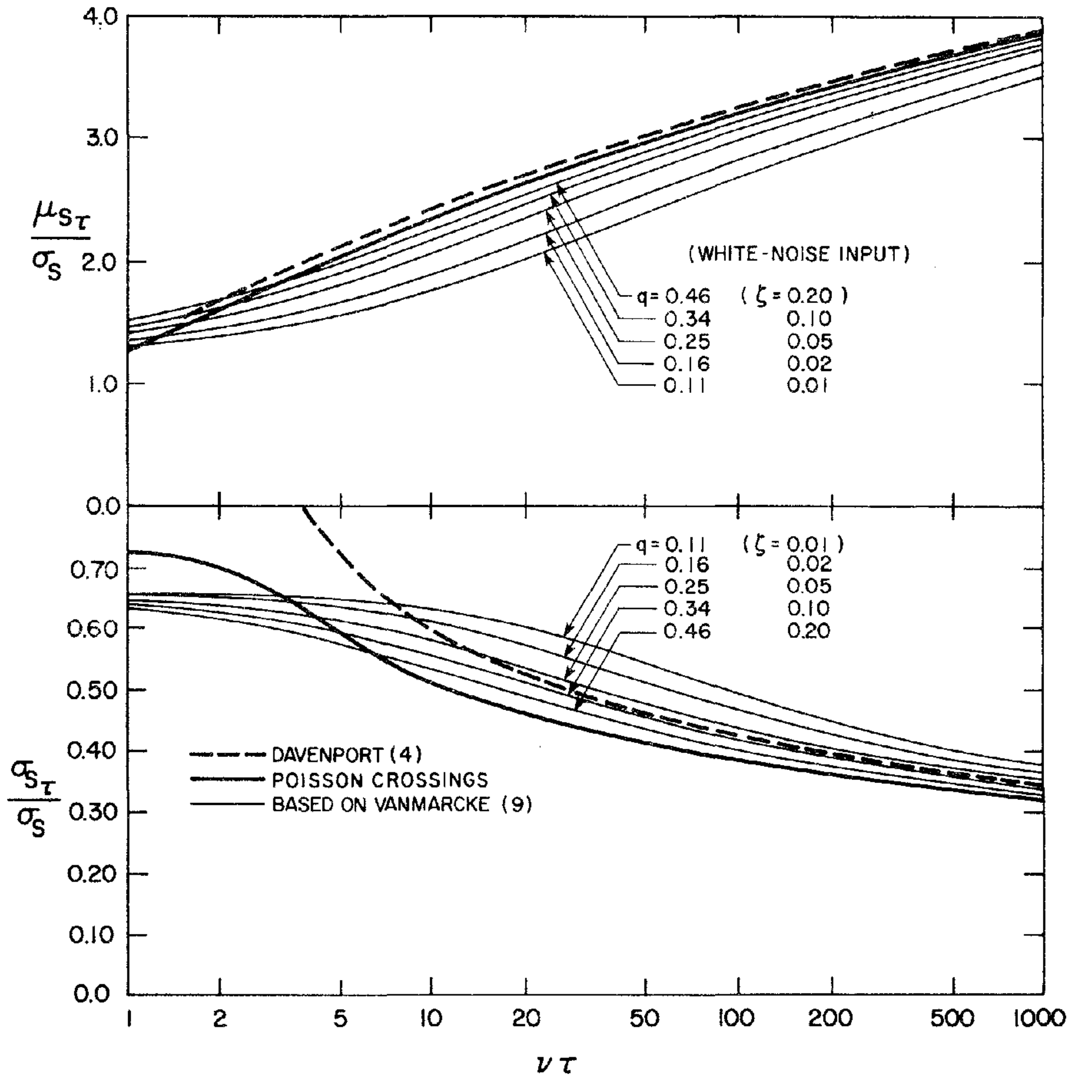


FIG. 1.- Normalized Mean and Standard Deviation of Peak of Stationary Gaussian Process

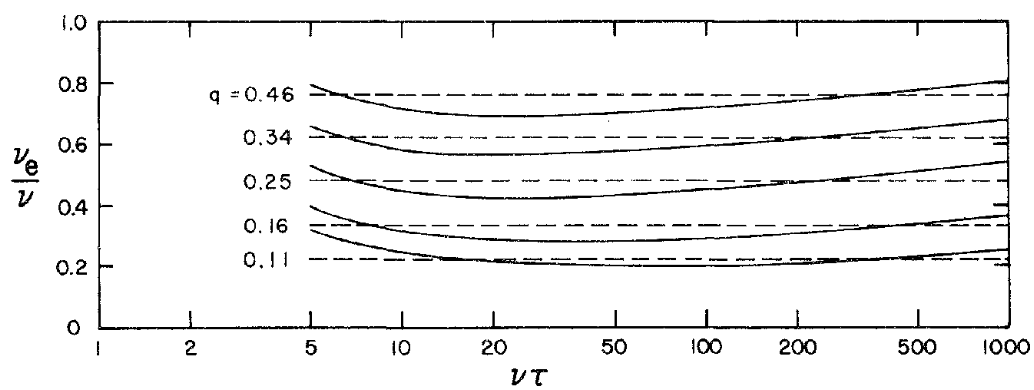


FIG. 2.- Ratio of Reduced to Mean Zero-Crossing Rate

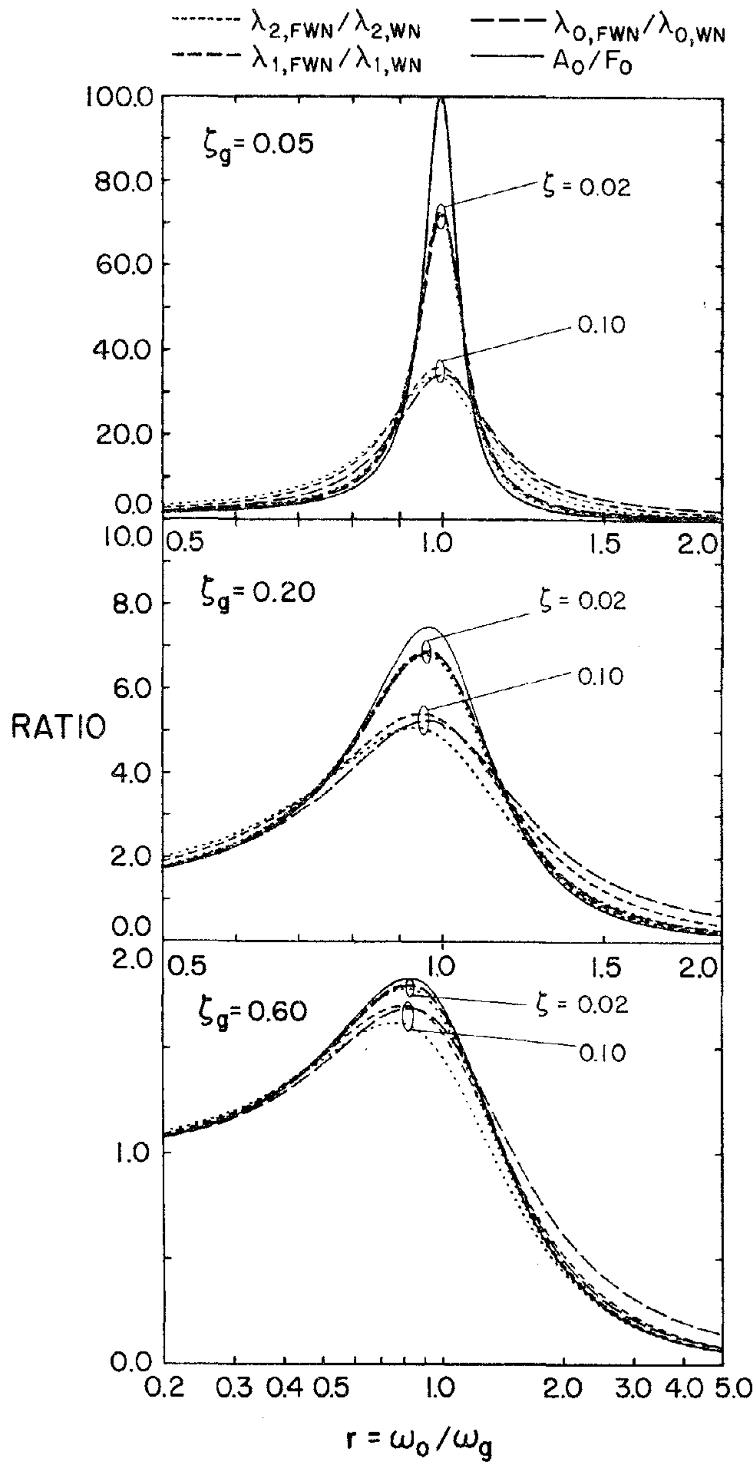


FIG. 3.- Ratios of Spectral Moments of Responses to Filtered White-Noise (FWN) and White-Noise (WN) Inputs

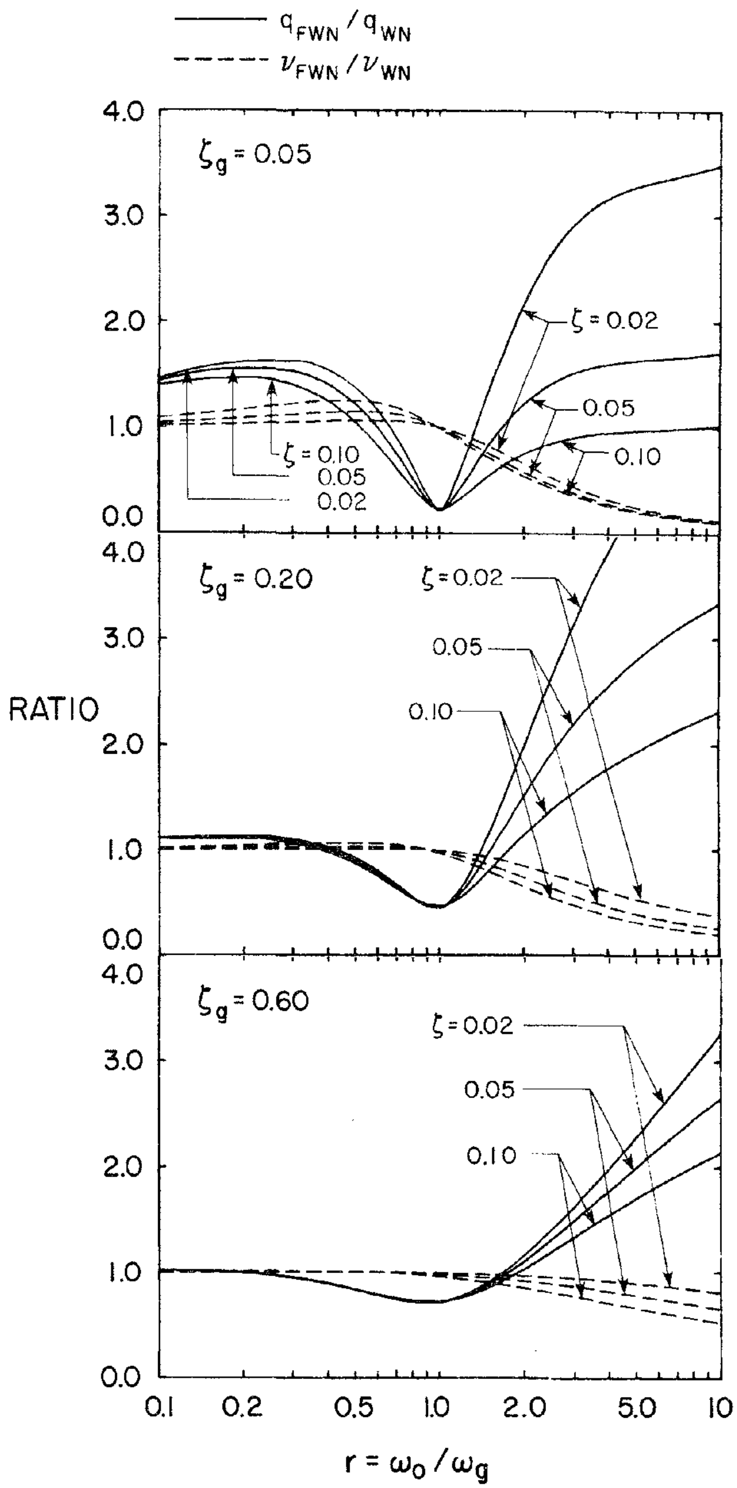


FIG. 4.- Ratios of ν and q for Responses to Filtered White-Noise (FWN) and White-Noise (WN) Inputs

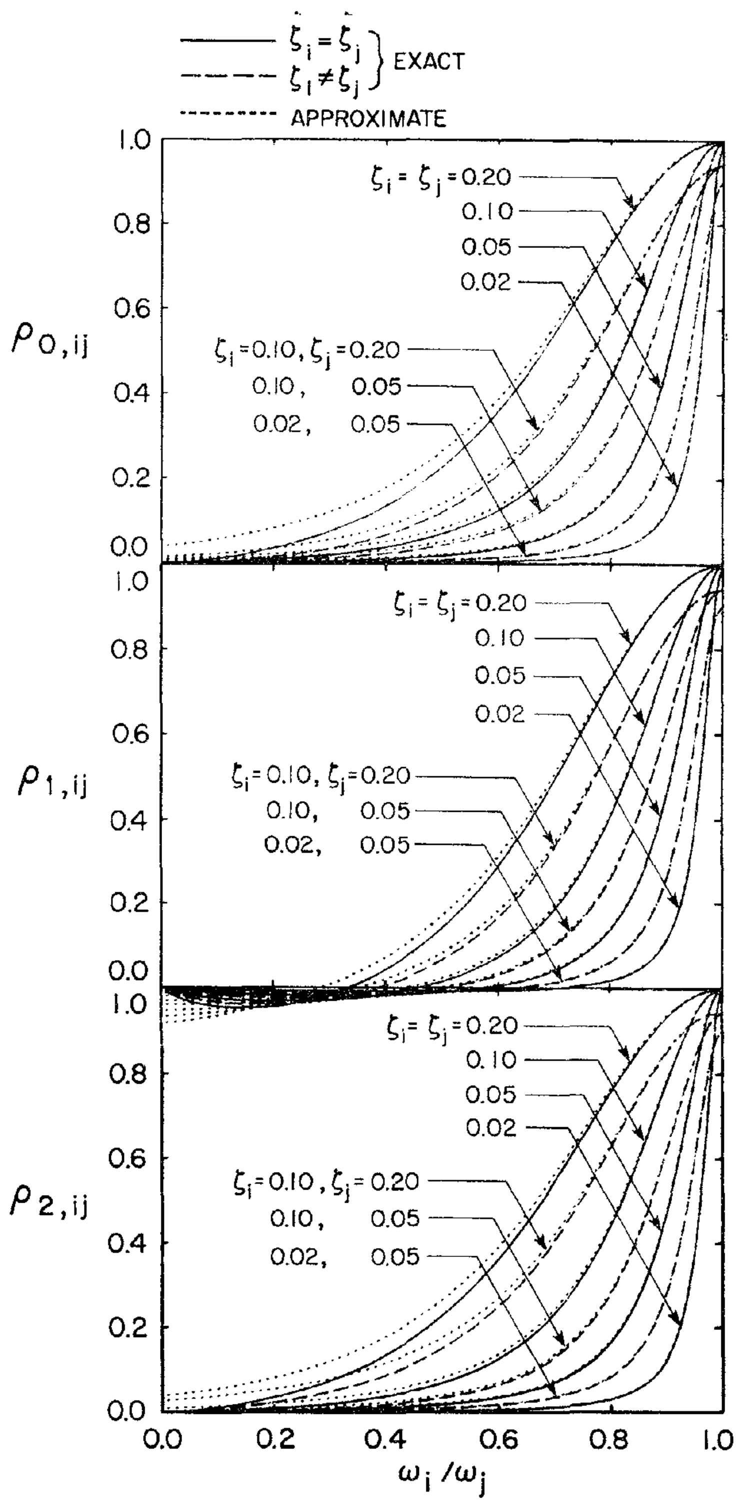
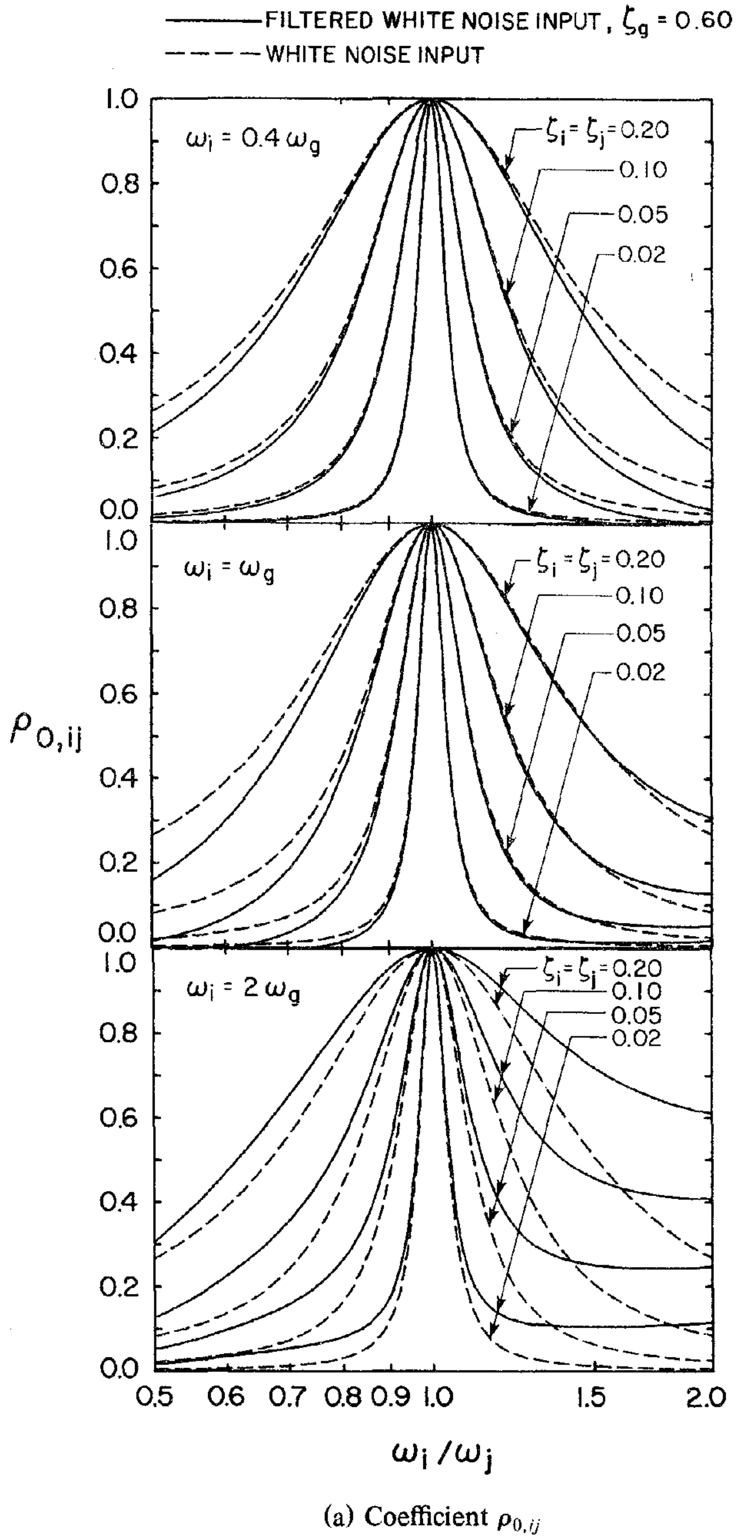
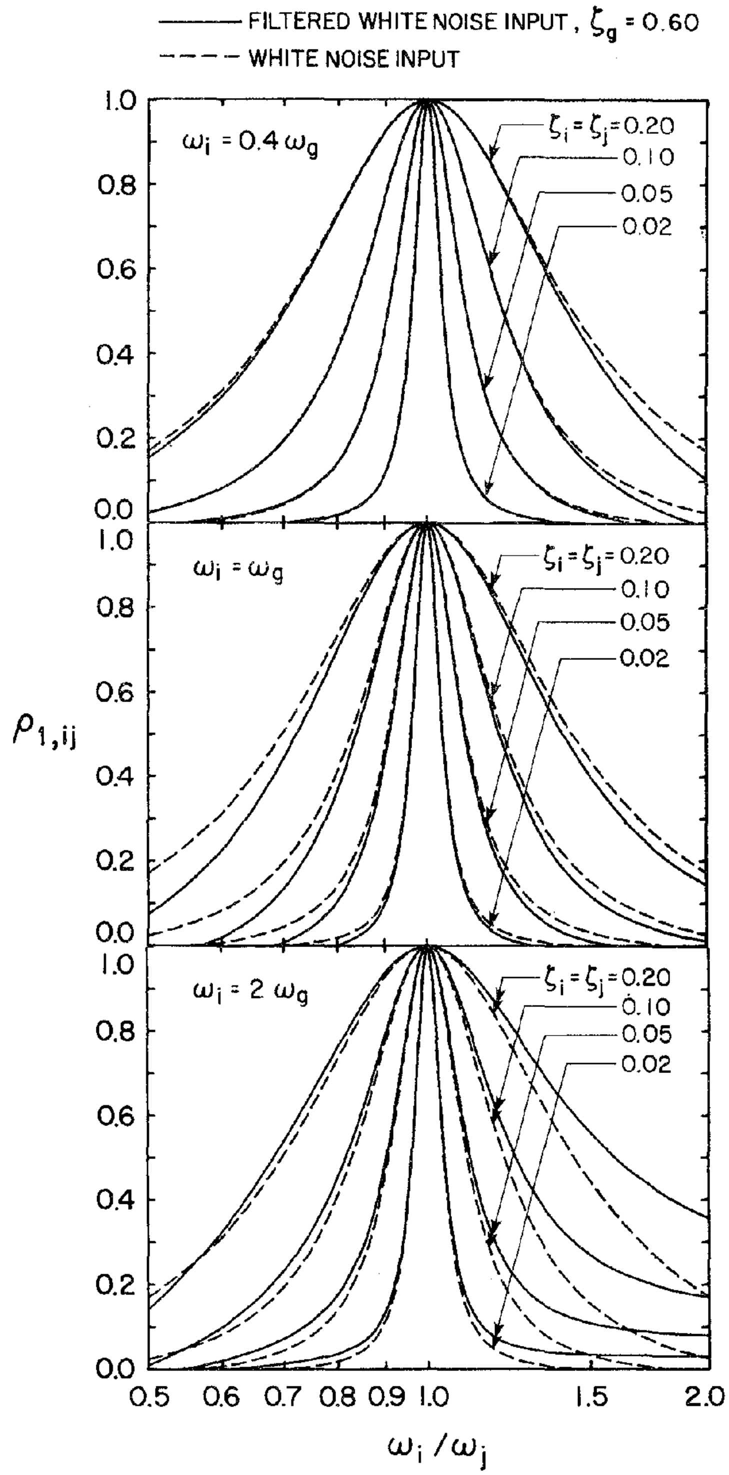


FIG. 5.- Coefficients $\rho_{m,ij}$ for Response to White-Noise Input



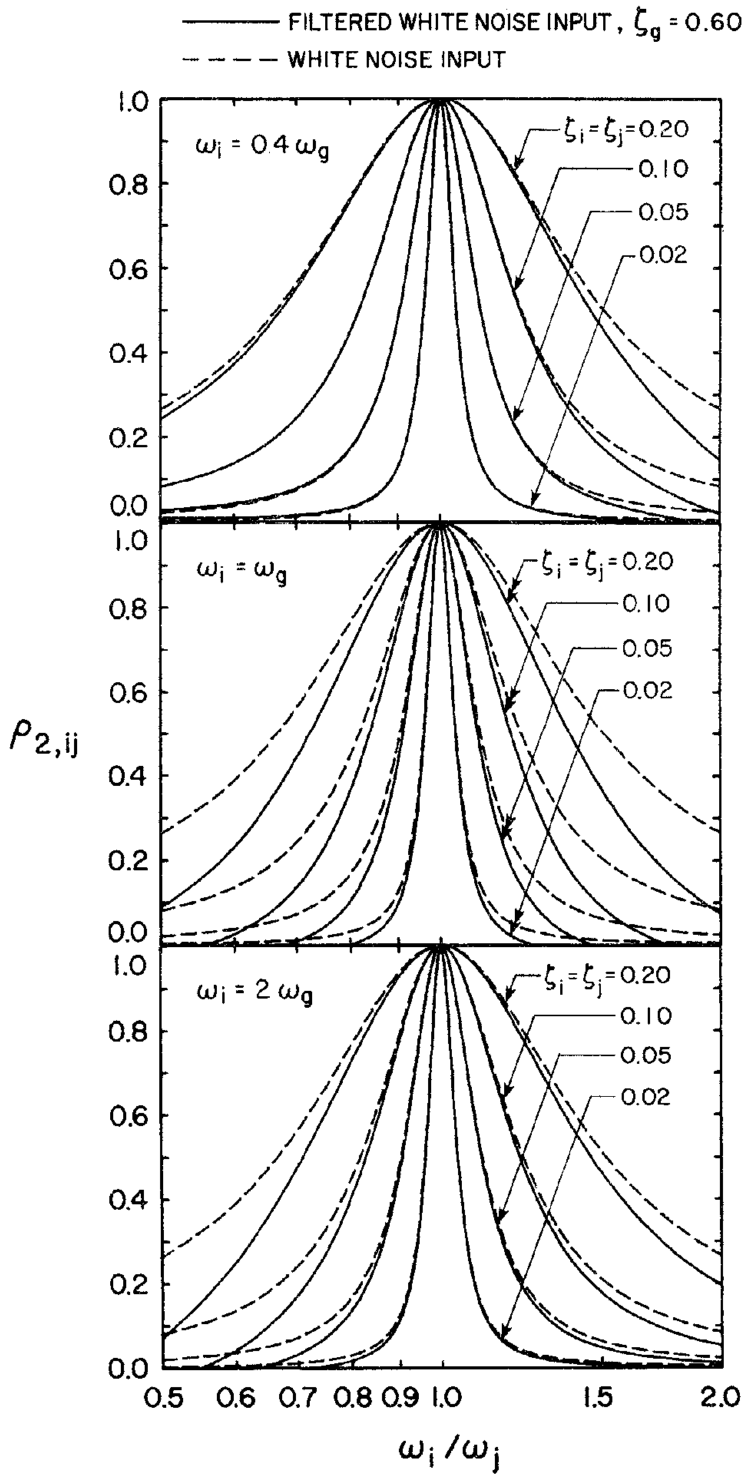
(a) Coefficient $\rho_{0,ij}$

FIG. 6.- Coefficients $\rho_{m,ij}$ for Response to Filtered White-Noise Input



(b) Coefficient $\rho_{1,ij}$

FIG. 6.- Continued



(c) Coefficient $\rho_{2,ij}$

FIG. 6.- Continued

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