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BROOKHAVEN NATIONAL LABORATORY REVIEW OF METHODS AND CRITERIA FOR DYNAMIC COMBINATIONS IN PIPING SYSTEMS, FINAL REPORT

FISCAL YEAR 1979*

Structural Analysis Group
Department of Nuclear Energy
Brookhaven National Laboratory

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ACKNOWLEDGEMENTS

This is the final report on the study of the methods and criteria for combining dynamic responses in piping systems. The study was carried out during the period October 1, 1978 to September 30, 1979.

During the course of this investigation, various people have contributed to the clarification of the basic issues involved in load combinations. In particular, we would like to acknowledge the assistance given by Dr. M. Shooman of the Polytechnic Institute of New York, Dr. S. Kao and Dr. M. Subudhi of the Brookhaven National Laboratory. Their work on the various phases of this work is greatly appreciated.

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I. INTRODUCTION

1.1 Background

Structures for nuclear power plant facilities etc., must be designed to have sufficient structural capacity to resist safely and effectively all types of load combinations that may be expected during their lifetime. These load combinations include both multiple dynamic loads as well as static loads. Specifically, the piping systems, as well as other pressurized components of the light water reactors (PWR or BWR), will be subjected to dynamic loads from various sources, such as earthquakes, loss-of-coolant accidents, safety relief valve actuations and vent chugging loads. The Nuclear Regulatory Commission has historically required that the responses due to these loads must be properly combined to insure the safety of these structural or mechanical components. In most cases, peak responses from each of the dynamic loads are first calculated and then subsequently combined to obtain a resultant peak combined dynamic response. Once the resultant peak combined dynamic response has been determined from a combination of the multiple peak dynamic responses, the resultant is added absolutely to the elastically calculated static response. This elastically calculated combined maximum response is then compared to code allowable stress levels, with the acceptance criterion being that the combined response must be lower than the code allowable level.

For some loading phenomena, the dynamic analysis provides a definitive time history response thus allowing for a straightforward addition of responses where more than one load is acting simultaneously. In other cases, no specified time phasing relationship exists, either because the loads are random in nature or because the loads have simply been postulated to occur together without a known or defined coupling.

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The basic problem involves the combination of two or more responses which are assumed to occur concurrently. This means that there is some degree of overlap between the signals. The second signal is assumed to occur some time after the start of the first signal. The only uncertainty is the relative starting time (time lag or phasing difference). Figure 1.1 depicts the combination for a particular time lag.

Where the time phase relationship is lacking, design engineers have utilized two distinctive methods to combine the dynamic responses. One method is called the Absolute Sum Method (ABS) by which the peak responses are added absolutely. The other is called the Square Root of the Sum of the Squares (SRSS) by which the combined result is equal to the square root of the sum of the squares of the individual resonse peaks. Depending on the relative magnitudes of the responses, the SRSS value will vary between about 0.7 ABS and 1.0 ABS for the combination of two dynamic responses. It is obvious that ABS represents the maximum possible combination result and may lead to overly conservative design requirements. On the other hand, the approach of SRSS is mainly based on heuristic reasoning, and is not supported by a rigorous mathematical proof.

Both General Electric and Westinghouse have carried out extensive studies in regard to the combination of dynamic responses for their respective reactor systems to support the validity of the SRSS method [1-2]. A working group was also formed in NRC to examine the problem of dynamic load combination and, in their report, further evaluations based on generic studies were recommended [3].

The Structural Analysis Group of Brookhaven National Laboratory was given a technical assistance contract for FY'79 by the Mechanical Engineering

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Branch, Division of Systems Safety of NRC to carry out the following: a) a generic study of the methods and criteria needed for appropriate combinations of dynamic responses in piping components and b) a study of the validity, adequacy, limitations and applicability of the two criteria for dynamic response combinations given in the General Electric report (NEDC-24010-2) entitled "Basis of Criteria for Combination of Earthquake and Other Transient Responses by the Square Root of the Sum of the Square Method."

The major tasks carried out under item (a) were:

1. Investigate the key parameters which can be utilized to fully characterize dynamic responses in the time and frequency domain. Parameters should include (but are not necessarily limited to) amplitude, frequency, phasing, and duration.

2. Develop the dynamic responses to two dynamic inputs for combination studies, both in the time and frequency domains, using the quantified parameters specified in Item 1. Conduct sensitivity studies by varying one or more than one of the parameters. The degree of influence of parameter variation on the results of response combination should be quantified. The method used to quantify the combination results may be in terms of non-exceedance probability or other appropriate means acceptable to the staff.

3. Based on knowledge obtained in sensitivity studies, develop recommendations for the combination of two dynamic responses, either expressed in the frequency domain or in the time domain.

Similarily, the major tasks carried out under (b) were:

1. Review the references cited in NEDO-24010-2.

2. Clarify the extent to which combinations of responses should only be based on the characteristics of the response time functions as opposed to the loading time functions. This clarification will be limited to computer runs with simple systems containing a few degrees of freedom.

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3. Using Monte Carlo simulation investigate the extent to which departures from zero mean affect the acceptability of the criterion.

4. Using Monte Carlo simulation, verify with real and simulated response functions whether the bases of limited number of high peaks (i.e., 5 or less exceeding 75% of maximum and 10 or less exceeding 60% of the maximum) is always acceptable. If not acceptable, determine alternate limitations.

5. Using Monte Carlo simulation, investigate the effect of the variation of signal duration time on the applicability of Criterion 1.

6. Using the Monte Carlo simulation, investigate--using various values of correlation coefficient--the acceptability of an equal or less than 0.4 value of correlation coefficient for the SRSS methodology.

b) for Criterion 2:

1. Review references pertaining to Criterion 2.

2. Using Monte Carlo simulation, verify with real and simulated response functions the degree of conservatism (or non-conservatism) obtained by accepting a 50% conditional probability that the actual peak combined response exceeds the SRSS calculated peak response.

3. Using Monte Carlo simulation, verify with real and simulated response functions the degree of conservatism (or non-conservatism) obtained by accepting a 15% conditional probability that the actual peak combined response exceeds approximately 1.2 times the SRSS calculated peak response.

This final report, which covers the period October 1978 to September 1979, is divided into eight sections. The present section, Section I, is intended to provide an introduction to the problem and to touch upon some aspects of the scope of the investigations. A summary of the conclusions from all sections is also given at the end of Section I. Section II details the available analytical methods and their limitations. This Section also describes some aspects of the

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numerical techniques developed to investigate and to carry out the objectives of the BNL study.

Section III details various aspects of combinations of sinusoidal responses which were initially studied to gain insight into the problem. The results of these studies are summarized under the headings: Summary of Conclusions for Sinusoidal Responses and Summary of Conclusions of Multisinusoidal Responses. The former deals with various forms of combinations of sinusoidal responses, while the latter deals with more complex forms that are somewhat similar in shape to those of real earthquakes.

Section IV deals with combinations of simulated responses in the frequency domain. The shapes of these responses were generated so that they closely resemble earthquake type of responses. Similarly, Section V deals with the particular effects related to the time domain. In this Section, the procedures and evaluations of simulated time-history response combination are discussed. The conclusions for Sections IV and V are, respectively, listed below under the titles: Summary of Conclusions for Artificial Responses in the Frequency Domain and Summary of Conclusions for Artificial Responses in the Time Domain.

Sections VI and VII detail the results of investigations regarding the acceptability of the two criterion for response combination set forth in the General Electric report NEDO-24010. Conclusions regarding Criterion 1 are listed under the heading Summary of Conclusions for General Electric NEDO-24010 Criterion 1, while those for Criterion 2 are listed under the title Conclusions for General Electric Report NEDO-24010 Criterion 2. Finally, in Section VIII, a suggested BNL criterion for response combination is presented. In our opinion, the BNL method considers all important aspects that contribute to the maximum response of the combinations and yet is relatively simple to apply.

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1.2 Summary of Conclusions for Sinusoidal Responses

1. Two identical sinusoids have combined responses based on SRSS at 50% non-exceedance level (NEP of SRSS at 50%).

2. Two different frequencies are a primary factor in reducing the percent of non-exceedance of SRSS.

3. Amplitude ratio is not a primary factor in changing the percent of non-exceedance of SRSS.

4. Increased damping will raise percent of non-exceedance of SRSS.

5. Density function for random phase angle is not a primary factor.

6. For random frequencies with normal distribution, an increase in σ lowers the percent of non-exceedance of SRSS.

7. More of the same sine waves will raise the percent of non-exceedance of SRSS.

1.3 Summary of Conclusions for Multisinusoidal Responses

1. Frequency relations of major components will affect percent of non-exceedance of SRSS, as is indicated in conclusions for sine response.

2. Number of peaks is a primary factor in determining percent of non-exceedance of SRSS.

3. Responses with the same components can give very different percent of non-exceedance of SRSS depending on phase angle of components.

1.4 Summary of Conclusions for Artificial Response in the Frequency Domain

1. NEP of SRSS decreases with increasing frequency bandwidth when predominant frequencies are same.

2. NEP of SRSS increases somewhat with smaller predominant frequencies.

3. NEP of SRSS decreases when predominant frequency differences increases.

4. NEP of SRSS may increase or decrease when the second response decreases in duration.

5. When both frequency and duration differences occur, NEP of SRSS may reach .30 to .40.

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1.5 Summary of Conclusions for Artificial Response in Time Domain

1. The larger the number of peaks passing the 60% and 75% of the maximum peak values, the lower will be the NEP of the SRSS. However, the peak count should be based on a rational scheme which includes the width (in time scale) of the peaks. In other words, peak count should reflect the percentage of the time of the response above a certain level of responses.

2. Based on the above reasoning, a more realistic approach appears to be that the NEP of SRSS is dependent on σ/R_{max} value of the individual responses where σ is the standard deviation of the digitized response distributions or,

$$\sigma_i = \left(\frac{\Sigma R_i^2}{N}\right)^{1/2} \quad ,$$

and R_{max} is the maximum absolute value of the peak response. As shown in the table, as the σ/R_{max} value grows, the NEP of SRSS becomes smaller.

3. The envelope shape of the response appears to play an important role. As the ratio of rising or decaying time to the duration of the signal increases, the NEP of the SRSS decreases.

4. When combining two signals, if the duration of the second signal is much shorter than the first one, then the combined response has a relatively low NEP of the SRSS.

1.6 Summary of Conclusions for General Electric Report--Criterion One, NEDO-24010

1. Response combinations should, generally, be based upon the charcateristics of the response time histories and not upon the loading time histories.

2. Monte Carlo computations show that in some cases, the non-exceedance probability of SRSS falls below 50% even when the requirements of Criterion 1

are met with the required number of peaks. Duration time of peaks is also an important factor that affects the NEP of SRSS.

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3. For the case of non-zero mean, the following formula can be used:

$$SRSS = \Sigma|\mu_i| + \sqrt{\Sigma(R_{i_{max}} - \mu_i)^2} ,$$

where μ_i is the mean and $R_{i_{max}}$ is the maximum value.

4. If the duration of one signal is very much shorter than the other, the chances for peaks to combine become less, and hence, the non-exceedance probability of the SRSS increases.

5. The correlation coefficient has no bearing on the SRSS role if random time lag is used in the combination.

1.7 Conclusions for General Electric Report, Criterion Two, NEDO-24010

1. Cumulative Distribution Function (CDF) constructed on the basis of absolute values of the combined results is slightly more conservative than the CDF curve which separates the positive portion and the negative portion.

2. The acceptable NEP level on the CDF should be preferably at the mean-plus-one standard deviation (approximately 84%).

3. In cases where the load specifications are rigorously determined at a conservative level (say, 84% probability level), based on all the factors influencing the response characteristic, then the acceptable NEP level may be lowered.

It should be noted that although we have made a run which resulted in verification of Criterion 2, we do not, however, consider the verification to be "all conclusive." The reason for this is that there are some ambiguities

in the load definitions at mean-plus-one standard deviation. Furthermore, the verification approach itself is not unique and, thus, the results are questionable.

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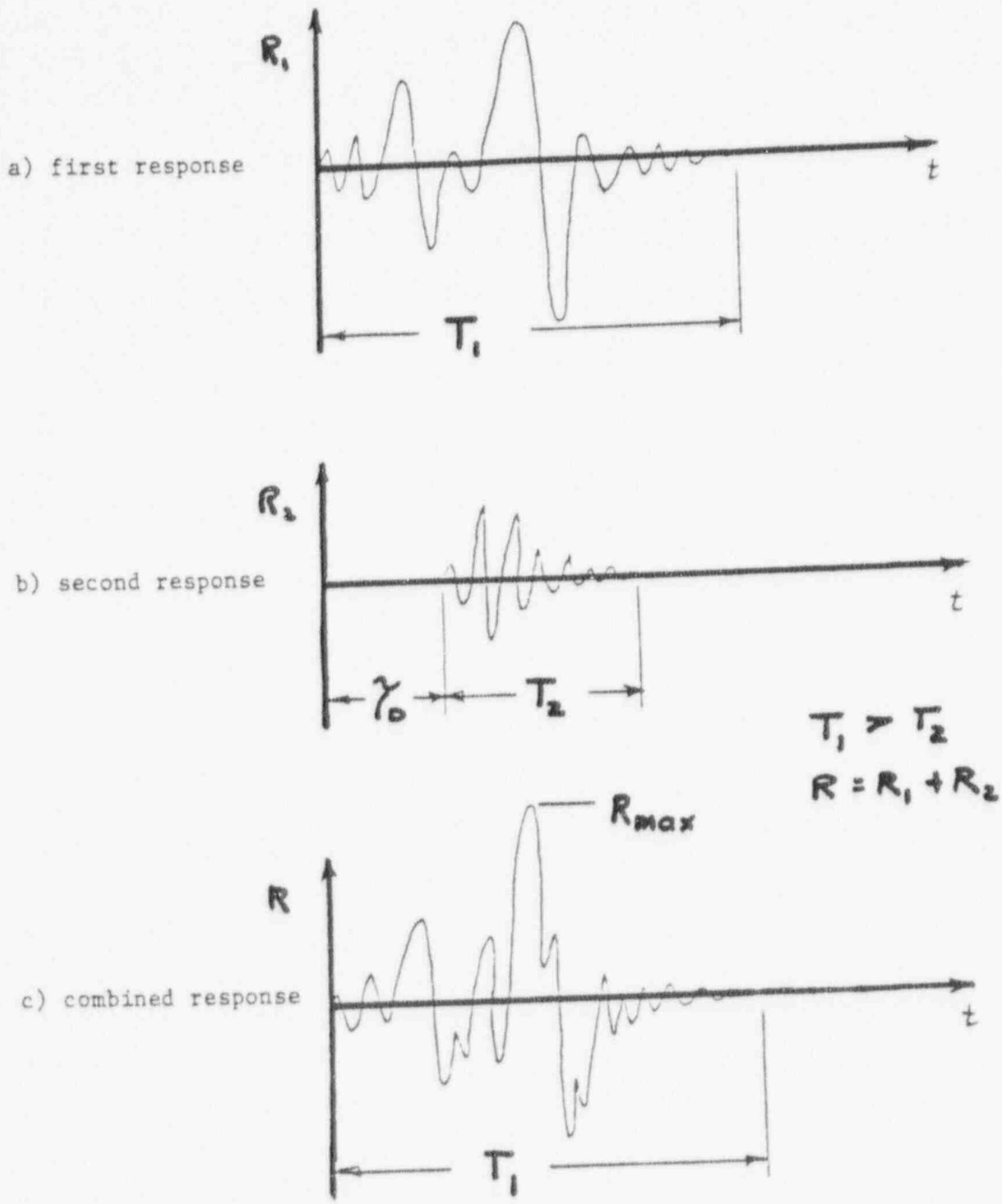

Fig. 1.1 Combining Responses with Random Time Delay, τ_D

II. METHOD FOR INVESTIGATION

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2.1 Analytical Approach

When two or more dynamic responses with random starting times are combined together, the mathematical expression of the probability distribution of the result can be written as follows:

$$R(t) = \sum_{i=1}^{n} f_i(t-\tau_i)$$
$$P\ (|R_{max}(t)| \leq y) = F(y) \tag{2.1}$$

where each component response, $f_i(t)$, may be taken as a non-stainary stochastic process, and τ_i is the random time lag with unknown probability distribution. The closed form solution of F(y) in general is extremely difficult to obtain. To gain insight into the problem, combinations of sinusoidal responses were initially investigated. The closed form solution of two combined equal frequency sinusoidal responses with random phase angle is given by the expression:

$$R(t) = A\sin\omega t + B(\omega t + \theta)$$

$$= C\sin(\omega t + \phi)$$

where θ is assumed to be uniformly distributed between 0 and π or the density function $f(\theta) = \frac{1}{\pi}$, and C, the resultant amplitude, is

$$C = \sqrt{A^2 + 2AB\cos\theta + B^2}$$

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The inverse relationship is $\theta = \cos^{-1}\left(\frac{C^2 - A^2 - B^2}{2AB}\right)$, while the absolute value of the derivative of θ with respect to C is $\left|\frac{d\theta}{dc}\right| = \left|\frac{C^2}{AB\sin\theta}\right|$, thus the density function of the absolute value C i.e., g(c) is

$$g(c) = f(\theta) \cdot \left|\frac{d\theta}{dc}\right| = \frac{1}{\pi} \frac{2C}{\sqrt{4A^2B^2 - (C^2 - A^2 - B^2)^2}} \tag{2.2}$$

The plot for the case where A is equal to B is shown in Fig. 2.1. Similarly the plot for the case where A = 2B is shown in Fig. 2.2. The cumulative distribution functions (CDF) for the two cases are also shown in the respective figures. It is to be noted that the nonexceedance probability (NEP) of SRSS for both cases is 0.5 i.e.,

$$\text{NEP of SRSS} = \frac{1}{2} \tag{2.3}$$

When the frequencies of the two sinusoids differ significantly, it is expected that the combined response peak will approach the absolute sum of the individual amplitudes with a high probability. This means that the nonexceedance probability of SRSS will be lower than $\frac{1}{2}$. An approximate solution for the case of the combination of two sinusoids with normally distributed frequencies has been formulated. Each frequency is defined to have a mean value μ_ω and standard deviations σ_i. As shown by the derivation given in Appendix F, NEP of the SRSS is given by

$$P(R \leq SRSS) = -\frac{1}{2} + \Phi\left(\frac{\pi}{T(\sigma_1^2 + \sigma_2^2)^{1/2}}\right)$$

$$-\frac{T\sqrt{\sigma_1^2 + \sigma_2^2}}{\sqrt{2\pi^3}}\left[1 - e^{\frac{-\pi^2}{2T^2(\sigma_1^2 + \sigma_2^2)}}\right] \tag{2.4}$$

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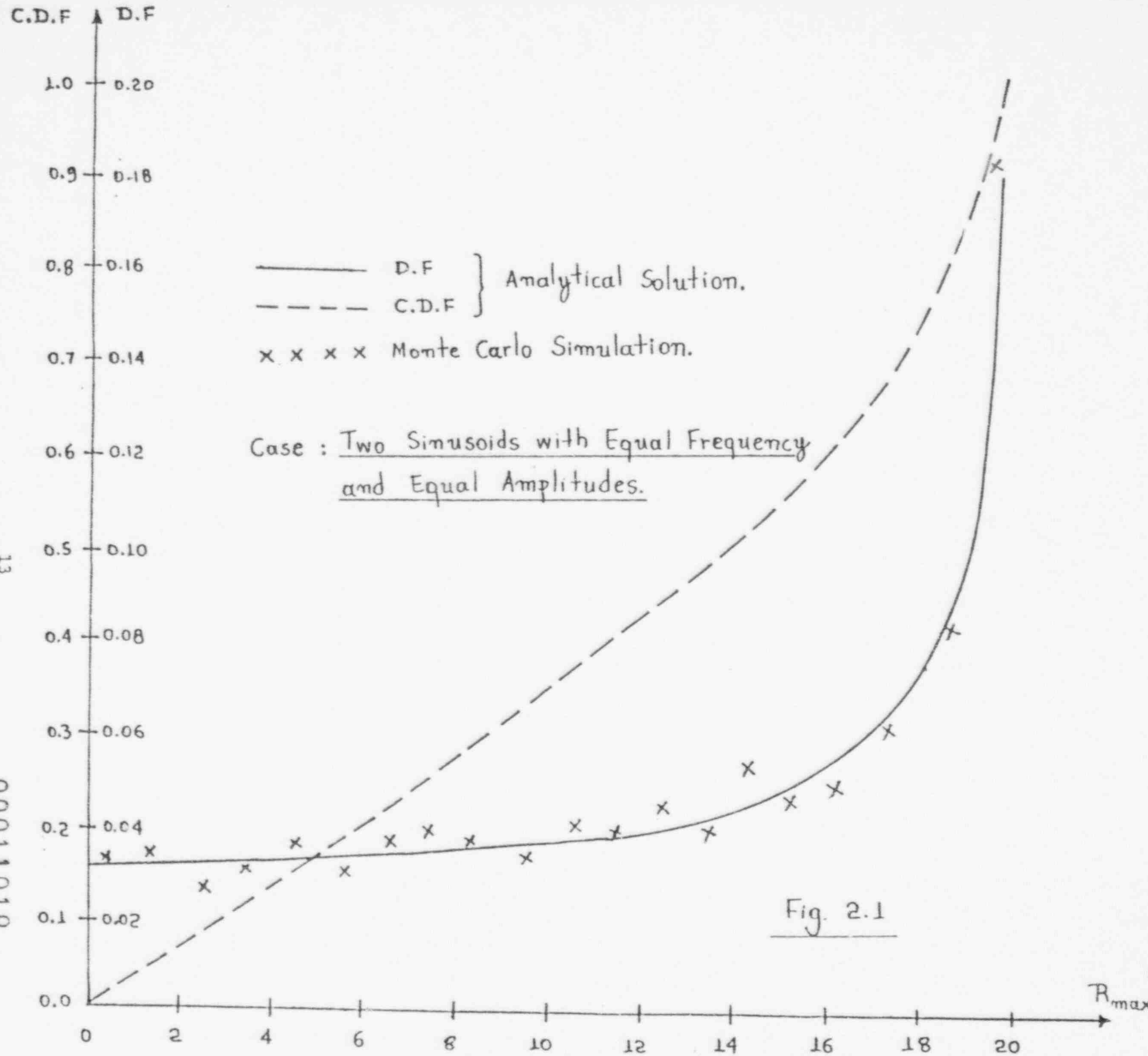

Fig. 2.1

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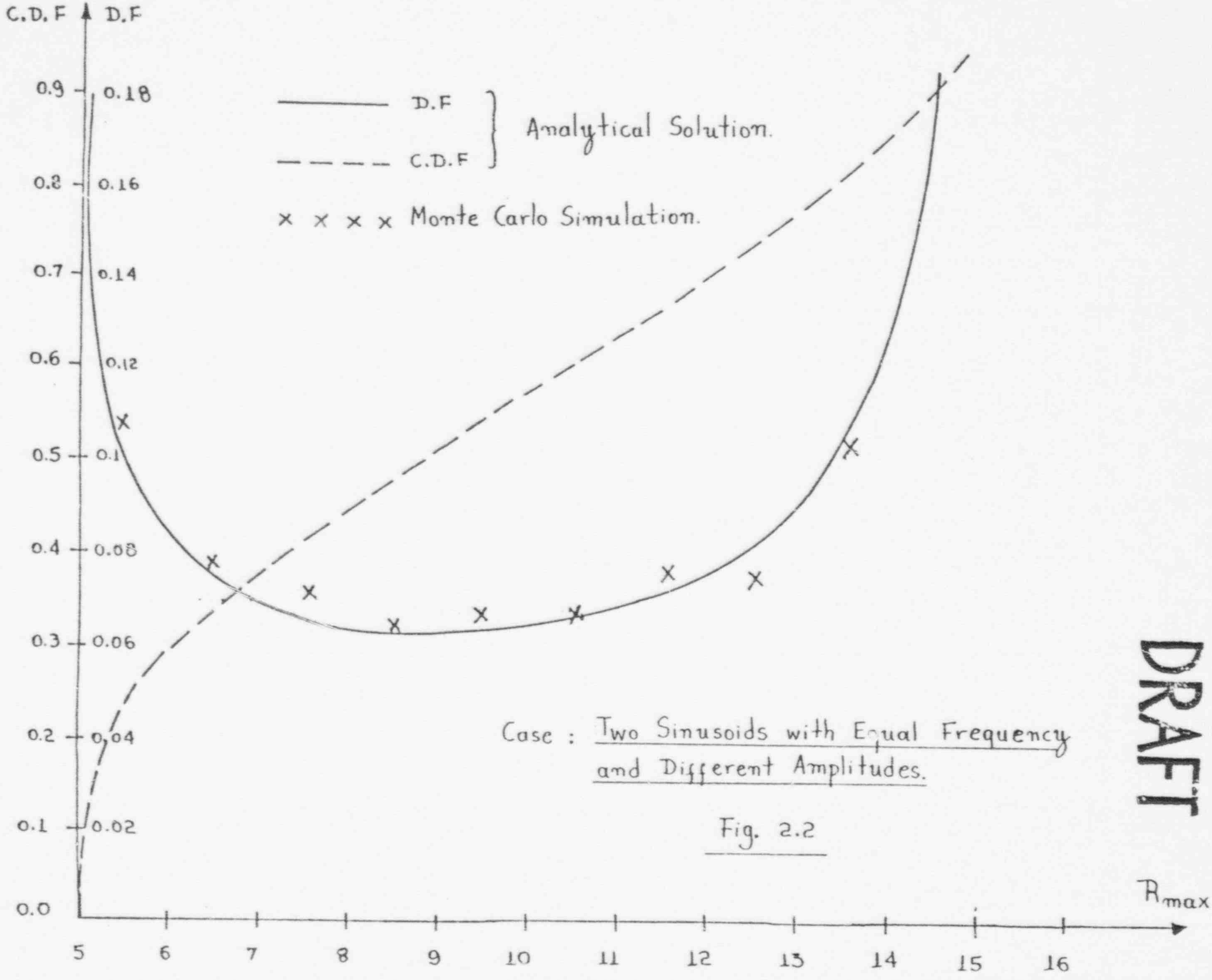

Case : Two Sinusoids with Equal Frequency and Different Amplitudes.

Fig. 2.2

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where T is the duration of both responses, σ_1 and σ_2 are the standard deviations of the frequency distribution and ϕ is the cumulative distribution function of the standard normal distribution. Equation 2.4 is subjected to the limitation that $\frac{T\sigma_1}{\mu_\omega}$ and $\frac{T\sigma_2}{\mu_\omega}$ are much less than 1. The analytical solution for the case where T = 5 and $\sigma_1 = \sigma_1 = 0.1$ is $P(R \leq SRSS) = 0.41$. Thus the introduction of randomness into the frequency serves to lower the R NEP of SRSS. In addition to this observation, the closed form solutions are important in that they provide checks for the numerical methods that had to be developed in order to solve the general problem of response combinations.

2.2 Monte Carlo Simulation

Since the closed form solutions for combining two or more general dynamic responses are extremely difficult to obtain, it was necessary to develop a numerical solution scheme. Specifically for the problems to be investigated under this study a Monte Carlo simulation computer code was developed. The capability of this simulation code encompasses all types of signals. This includes the combination of sinusoids, damped sinusoids, artificially generated signals such as earthquakes, SRV's or digitized real responses. The maximum number of signals that can be combined is limited to four for this investigation but can be increased. The distribution of the time lag or phase angle can be uniform, normal, centered triangular or skewed triangular. The flow chart of the code is shown in Fig. 2.3. The notations used in the flow chart are defined as follows:

T_i - Duration in seconds of i-th response

A_i - Amplitude of i-th response

ζ - damping ratio used

μ_ω - mean of the frequency distribution

σ_ω - standard deviation of the frequency distribution

f_i - digitized response values for the i-th response

θ_i - phase angle of the i-th response

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ω_i - frequency of the i-th sinusoid

τ_i - time lag in seconds of the i-th response

To verify the accuracy of the code, the random number generator was first validated by the procedure of two dimensional plotting as suggested in reference [2]. The combination of sinusoids was then carried out and checked against the closed form solutions discussed in the previous section (i.e., section 2.1). As can be seen from Fig. 2.1 and 2.2 the Monte Carlo results, designated by the points marked by the x's, match with the solid line which represents the closed form solution. A check of Monte Carlo simulation values obtained for the CDF and NEP of SRSS vs. closed form results for two responses with mean frequency $\mu_\omega = 7.5$, duration $T = 5$ and $\sigma_1 = \sigma_2 = 0.1$ is shown in Fig. 2.4. The result of $P(R \leq SRSS) = 0.43$ checks fairly closely with that of the analytical result which was equal to 0.41.

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FLOW CHART

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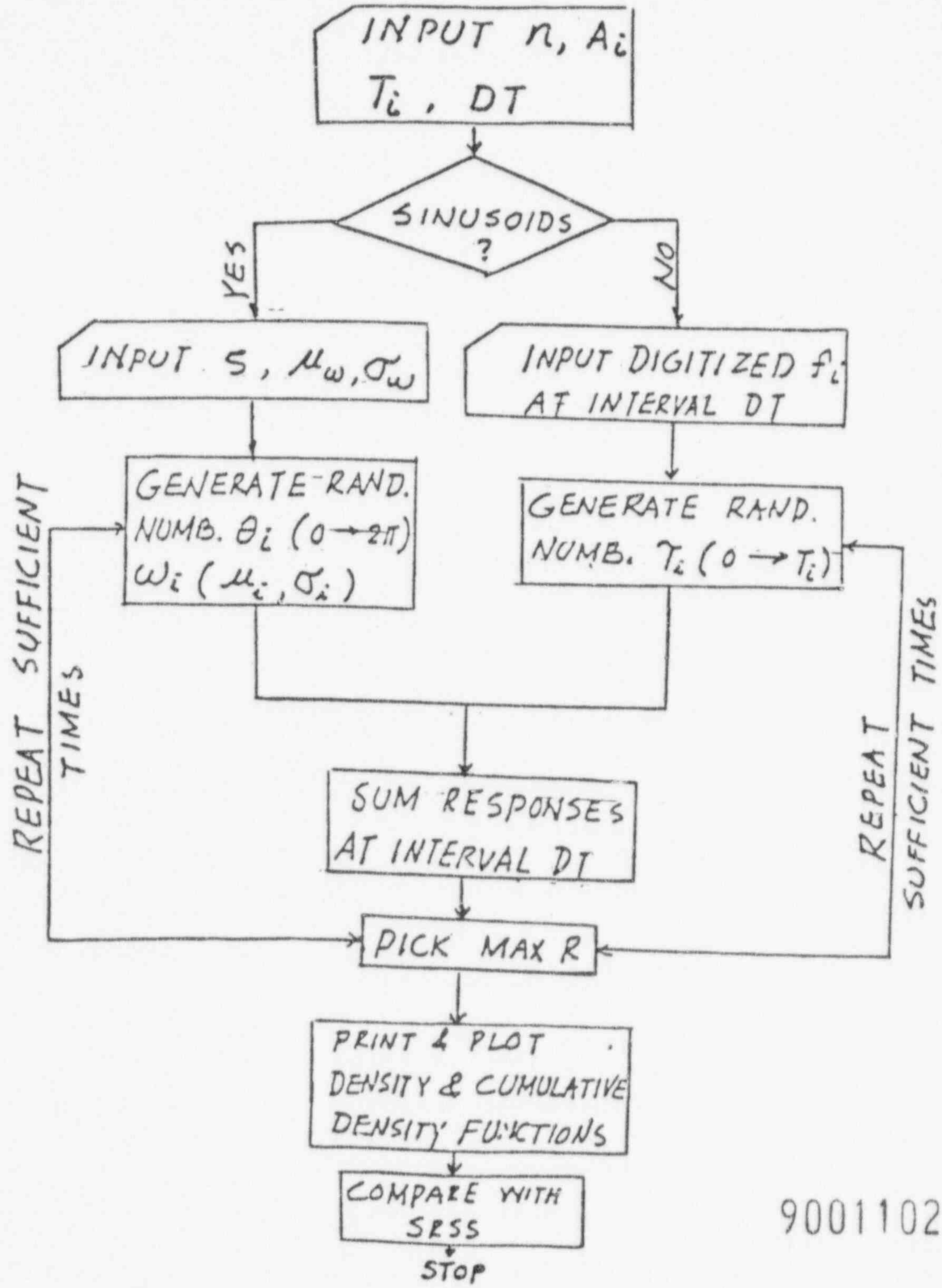

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Fig. 2.3 Monte Carlo Combination of Dynamic Responses

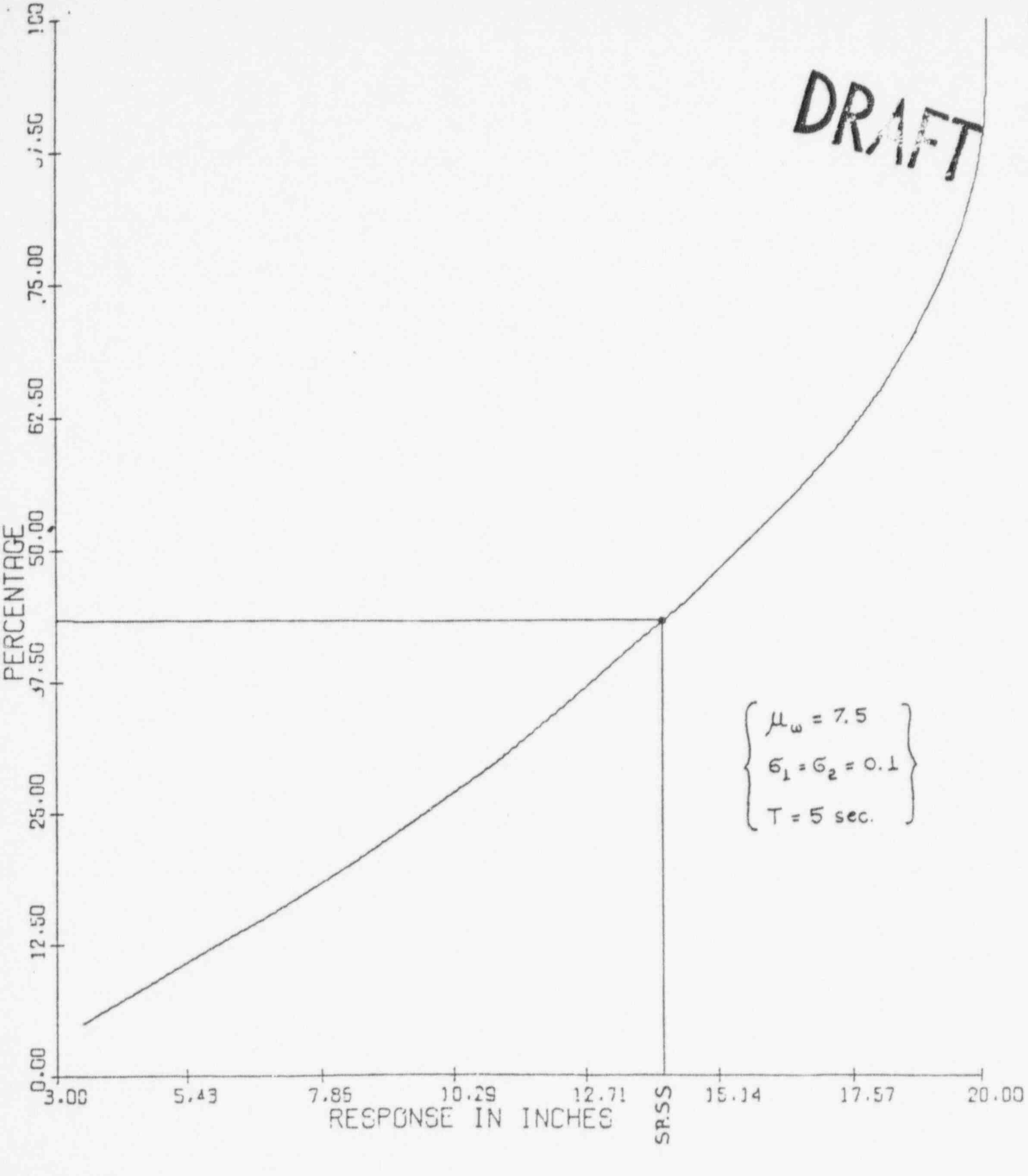

Fig. 2.4 2 SINE WAVES. EQUAL DURATION, DIFF FREQ...

III. COMBINATION OF SINE RESPONSES

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3.1 Basic Study

There is no general closed form mathematical solution that could be used for guidance in determining the degree of conservatism regarding the combination of randomly occurring signals by the absolute sum method. The absolute sum is a bounding case. This is all that is known. The degree to which departures in the absolute sum procedure may be used safely, and the restricting conditions that should be imposed, is the subject of this section. Only simple sinusoidal type signals are used.

The entire question of combining signals that arise from different transient sources is an easy one to answer if the procedure of adding the maximums of the separate signals is used and if the added conservatism does not unbalance other aspects of the design. The combined response in a linear system cannot exceed this sum. The difficult problem of response combination arises if a more precise definition of the probable bounds of the actual combination is attempted.

The first part of this study was intended to develop some understanding of the basic mechanisms involved in combining signals; which parameters in signal combination are of primary importance in affecting the maximum magnitude of the combination and which parameters are of only secondary importance.

Accordingly, the first part of this study was done with simple type signals with known properties, such as sine waves. Sensitivity studies were carried out by changing one or more of the parameters. Special selected cases were used to identify the important parameters. The general form of the basic combinations studied is

$$R(t) = \sum_{i=1}^{n} A_i e^{-\alpha_i t} \sin \omega_i (t-t_o) \qquad (3.1)$$

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Sensitivity studies were carried out to examine the effect on the maximum value of R(t) for each of the parameters in Equation 3.1. This includes:

a) A_i - the amplitudes of the signals

b) ω_i - the frequencies

c) t - the relative times of the signals

d) α_i - the damping

e) t_D - phase relationship or time lag

f) R(T) - the response combination

3.2 Two Sine Responses - Equal Frequency

For the case of two equal frequency sine waves, without damping, the general equation can be expressed in the form previously given in Section 2.1, i.e., $R(t) = A_1 \sin \omega t + A_2 \sin \omega(t - t_D)$. The amplitude ratios were changed over a range from 1 to 10. The time delay was selected randomly to have a value no greater than a full period of the first signal. For the first series of tests, the distribution of ωt_D was assumed to be uniform. Subsequently, different types of distributions for time lag were also investigated. Three different choices for the random phase angle, ωt_D, were selected

1) uniform from 0 to 2π

2) triangularly distributed from 0 to 2π with mean θ_μ at π

3) normally distributed with $\theta_\mu = \pi$, $\sigma = \frac{\pi}{4}$

These studies were intended to determine whether an accurate assessment of the nature of the randomness was important to the combined result.

For each selection of the values of the two sine waves, a Monte Carlo computation was carried out. The cumulative distribution function (CDF) curve was plotted and the value of the square root of the sum of squares (SRSS) was superimposed. The results are listed in Table 3.1.

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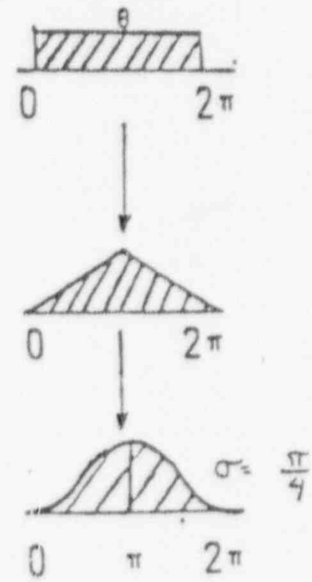
Combinations of Equal Frequency Sine Waves

TABLE 3.1

Case No.	Amplitudes A_1, A_2	Frequencies rad/sec	Duration Time, sec.	(NEP) $P(R \leq SRSS)$ %	Phase Angle ωt_D
1	10, 10	10, 10	5, 5	52	
2	10, 10	7.5, 7.5	5, 5	52	
3	10, 5	7.5, 7.5	5, 5	52	
4	10, 1	7.5, 7.5	5, 5	52	
5	10, 10	7.5, 7.5	5, 5	42	
6	10, 5	7.5, 7.5	5, 5	40	
7	10, 1	7.5, 7.5	5, 5	40	
8	10, 10	10, 10	5, 5	52	
9	10, 10	10, 10	5, 5	50	



The results show that, for equal sine waves, the combined responses have a non-exceedance level of SRSS at about 50%. This is in accordance with the closed form analytical results that were obtained and discussed in Section 2. Changing the amplitude ratio over a wide range, from 1 to 10, does not affect the result and the $P(R < SRSS)$ is still at about 50%, as seen by Cases 2, 3, and 4 of Table 3.1. When other types of distributions are used to describe the randomness of the time delay, these conclusions are not materially changed. Figures 3.1 through 3.7 show a plot of the percent non-exceedance of the SRSS for some of the cases in Table 3.1.

3.3 Two Sine Responses - Different Frequencies

The effects of changing the frequence ratio between the two sinusoidal components was next examined. It is known that if the two frequencies are greatly different, ultimately they will add absolutely if they persist long enough.

Frequency ratios were varied over a range of one to two. The frequencies were also chosen on a random basis with each frequency having a mean value and a normally distributed standard deviation. The standard deviation was also

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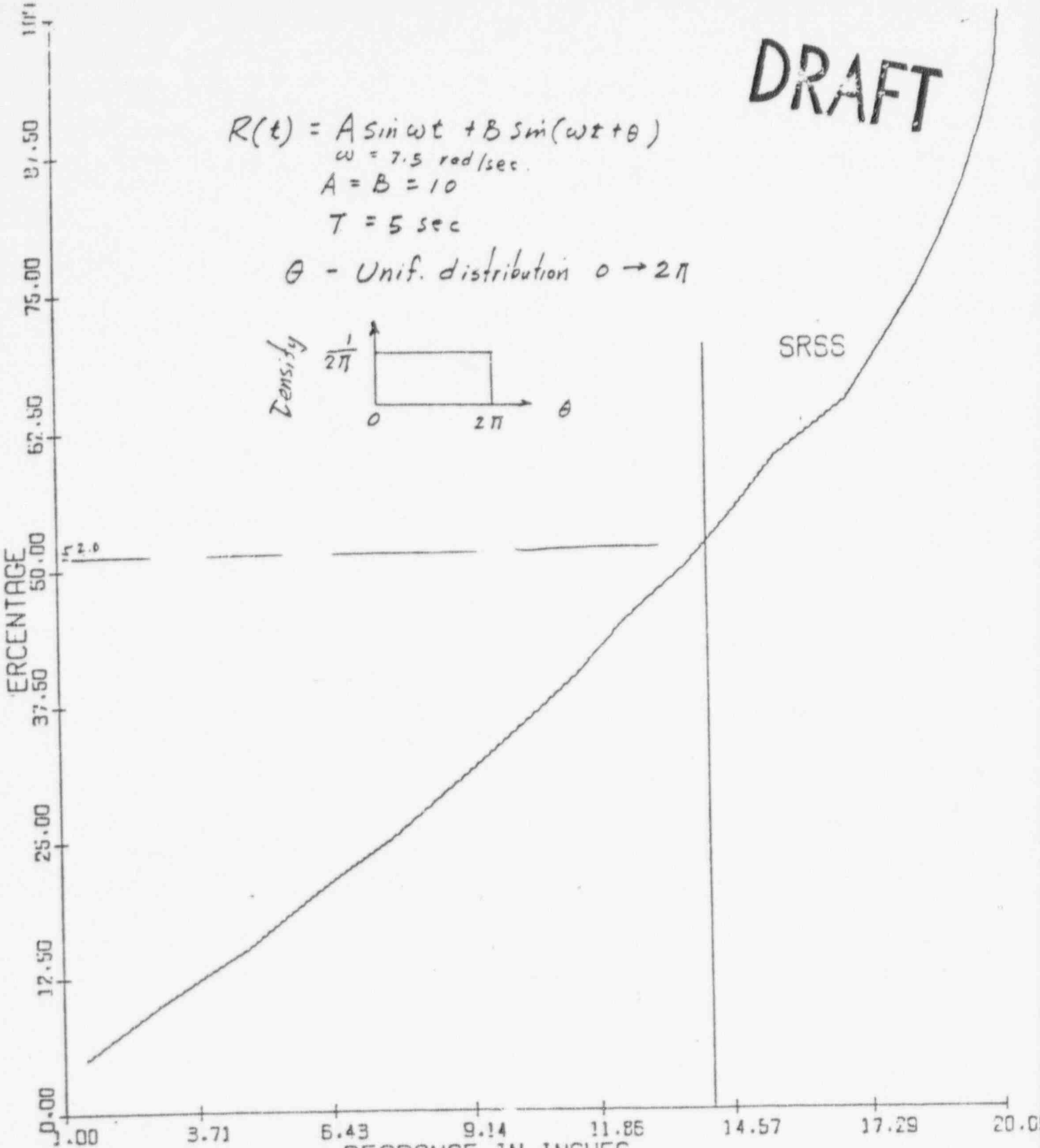

2 SINE WAVES. EQUAL FREQ. EQ. AMP. (A=B)

Fig. 3.1

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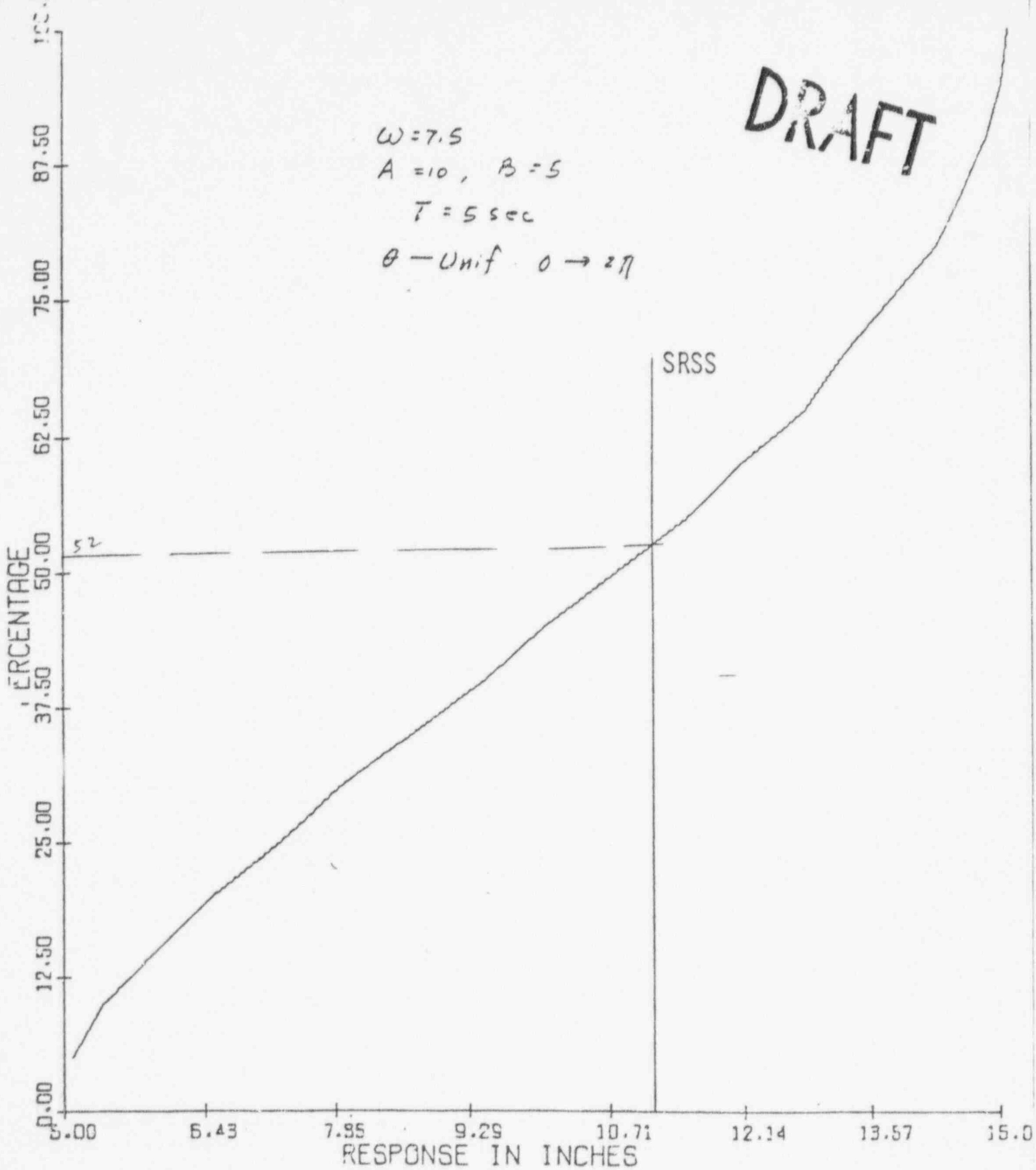

2 SINE WAVES, EQUAL FREQ, VARY AMP. (A=2B)

Fig. 3.2

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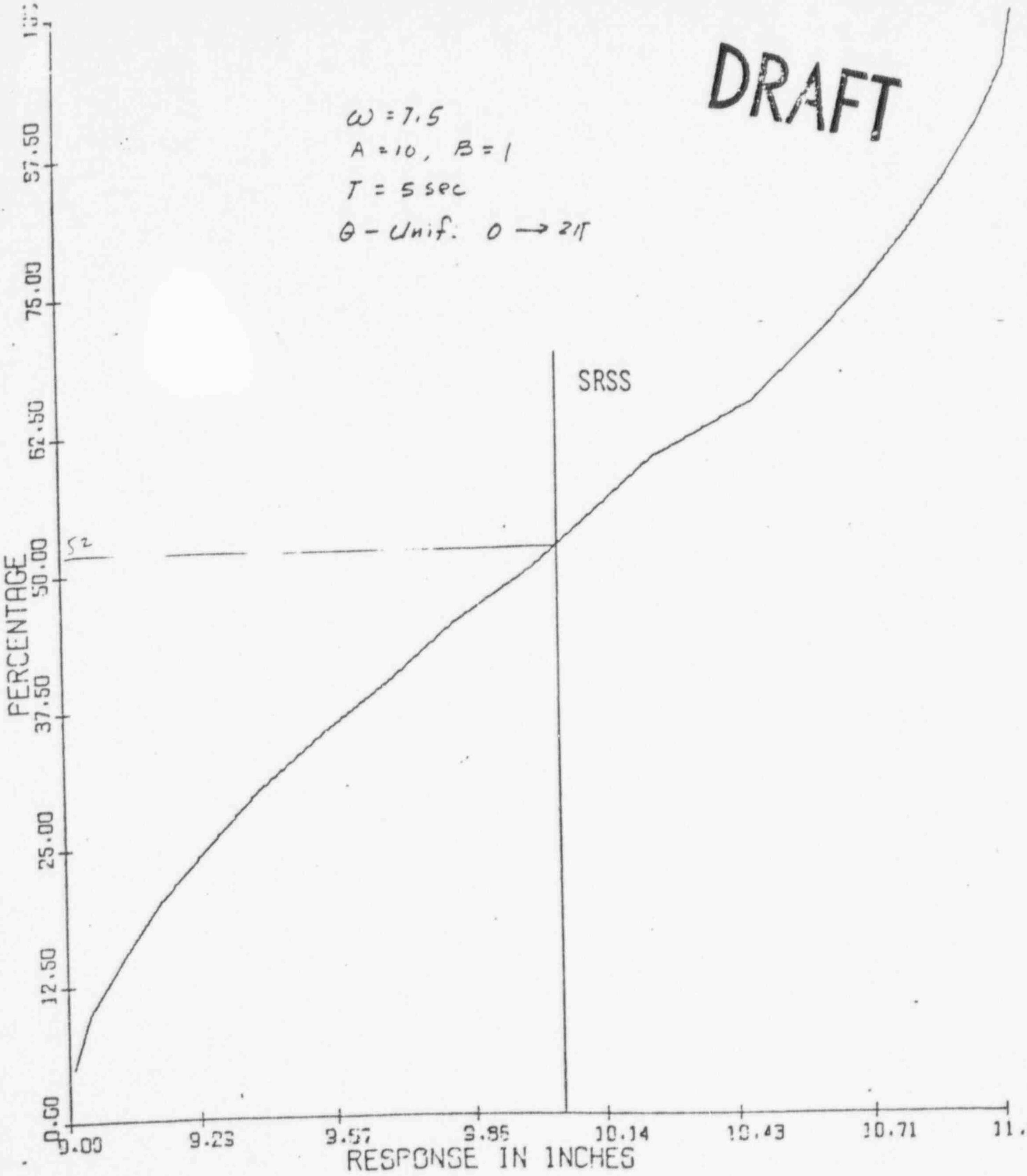
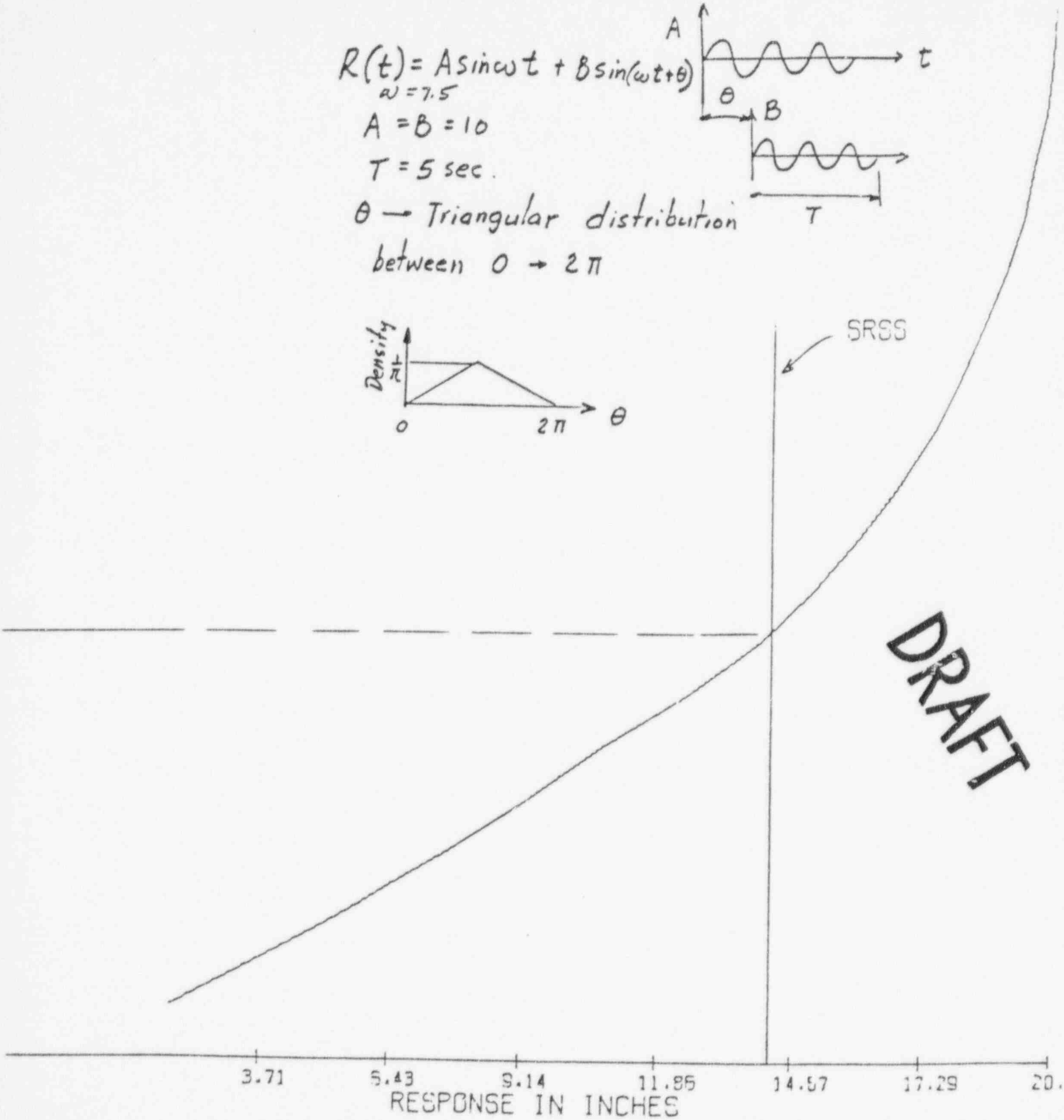


2 SINE WAVES. EQUAL FREQ. VARY AMP. (A=10B)

Fig. 3.3



2 SINE WAVES, EQUAL FREQ. EQ. AMP. (A=B)

Fig. 3.4

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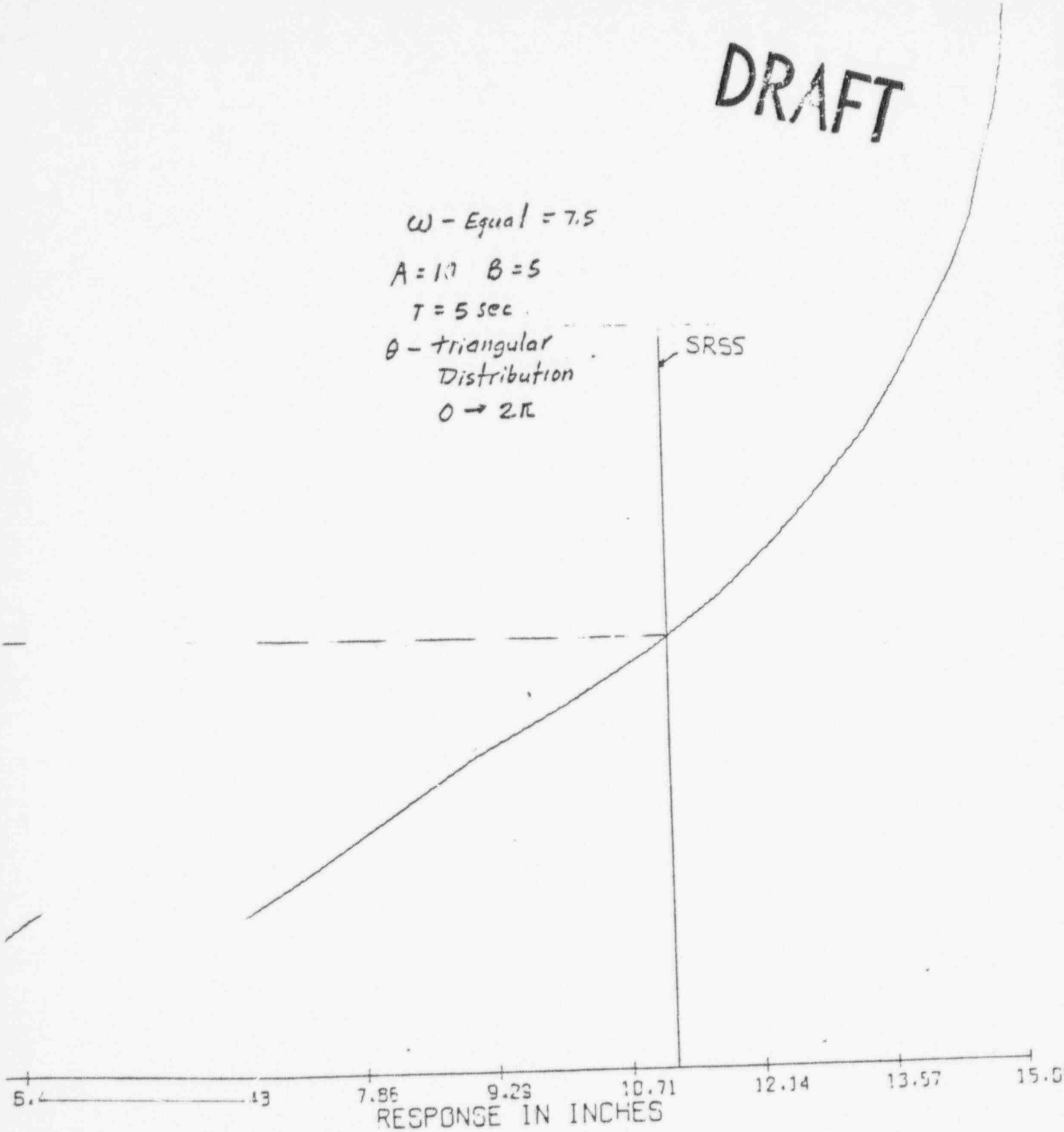

2 ——— 2 SINE WAVES, EQUAL FREQ, VARY AMP. (A=25)

Fig. 3.5

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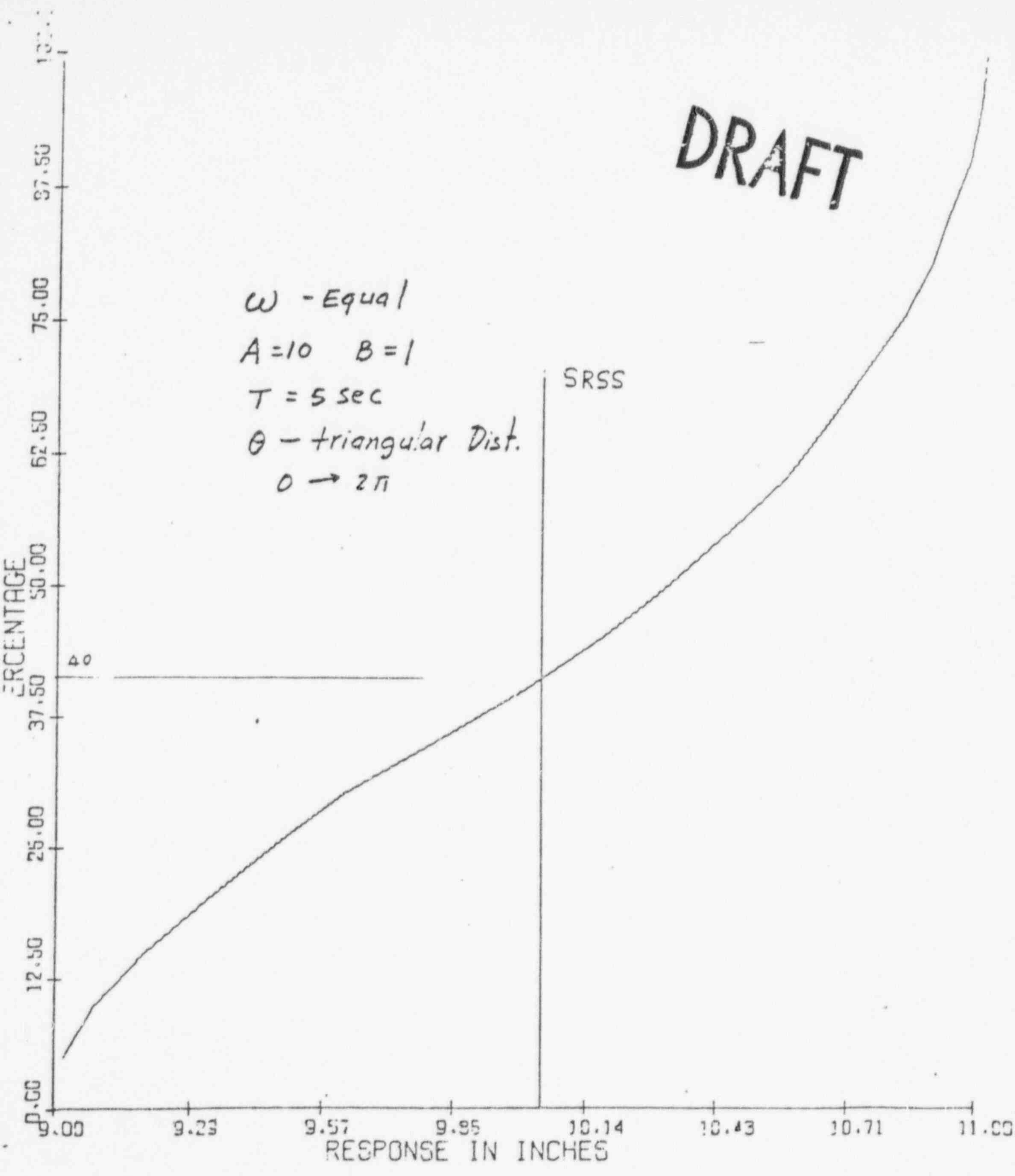

2 SINE WAVES, EQUAL FREQ, VARY AMP. (A=10B) (TRI.)

Fig. 3.6

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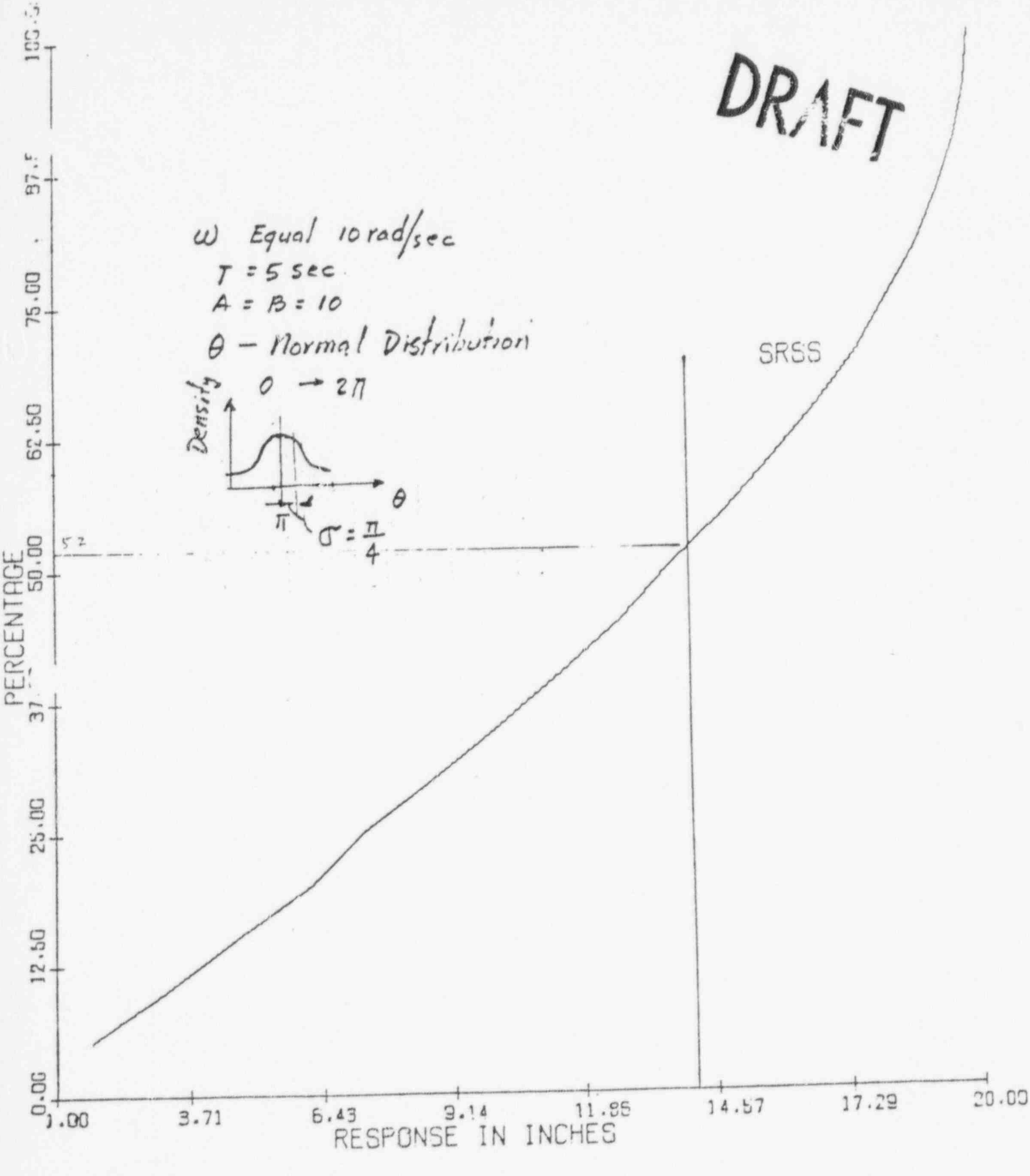

2 SINE WAVES. EQUAL DURATION.FREQ.AMP..GAUSSIAN

Fig. 3.7

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varied in separate cases over a range of values. The results are listed in Table 3.2.

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Combinations of Different Frequency Sine Waves

TABLE 3.2

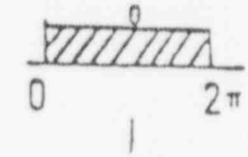
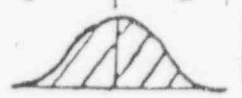
Case No.	Amplitudes A_1, A_2	Frequencies	Duration	NEP SRSS %	Phase Angle
10	10, 10	10, 5	5, 5	14.1	
11	10, 5	10, 5	5, 5	11.8	
12	10, 10	$\omega_{\mu_1}=\omega_{\mu_2}=7.5$ $\sigma_1=\sigma_2=.5$	5, 5	19	
13	10, 10	$\omega_{\mu_1}=\omega_{\mu_2}=7.5$ $\sigma_1=\sigma_2=.4$	5, 5	33	
14	10, 10	$\omega_{\mu_1}=\omega_{\mu_2}=7.5$ $\sigma_1=\sigma_2=.2$	5, 5	42	
15	10, 10	10, 5	5, 5	14.1	
16	10, 5	10, 5	5, 5	11.1	

Table 3.2 shows that the frequency ratio between the two sinusoids plays a primary roll in the non-exceedance probability of the SRSS. Comparing Case 1, from Table 3.1, with Case 10, the NEP has been reduced to 14%, a reduction of more than 3 to 1. Whether the amplitudes were the same or different and indeed, regardless of the assumption on the nature of the time delay distribution, the same sizeable reduction occurred. With a 2 to 1 frequency ratio that lasted for 5 seconds, the P(R < SRSS) was about 14% whether the amplitude ratio was 2 to 1 or 1 to 1 and whether the random distribution of the time delay was uniform, triangular or normal.

3.4 Combinations of More Than Two Sine Responses

Combinations of three and four sine waves were examined. The same kind of changes in amplitude and frequency as those of Section 3.3 were introduced.

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The time durations of the various components were also changed. This was done by introducing zero values for the signal after the duration time had elapsed. The results are also shown in Table 3.2.

Table 3.3 shows that the NEP of SRSS has increased somewhat with more terms. The same general conclusions that were previously obtained still hold. The introduction of a normally distributed frequency content lowers the P(R < SRSS) from 62 perent to 28 percent with three sinusoidal components and from 66 percent to 35 percent with four sinusoidal components. The change in duration time has also lowered the P(R < SRSS) somewhat for these cases.

3.5 Combinations of Damped Sinusoidal Responses

The final investigation in this basic series, introduced damping into the responses that were to be combined. Studies were made of the effects of frequency content, more than two response signals and different time durations. The shorter time durations were again accomplished by curtailing a signal and assigning a zero value after that time. These are listed in Table 3.4.

The results show that the essential effect of damping is to increase the P(R < SRSS). For example, with 2 percent of critical damping, Case 25 shows an increase of 3 percent over the corresponding problem in Case 3. It can be expected that as damping is increased, the NEP of SRSS will also increase. The same conclusions are indicated for cases involving the combination of more than two responses.

3.6 Conclusions for Combining Sine Responses.

The conclusions that can be drawn from the investigation of sinusoidal responses can be summarized as follows:

1. Two identical sinusoids have combined responses at 50% non-exceedance level

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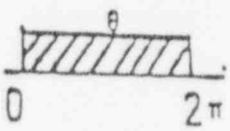
Combinations of More Than Two Sine Waves

TABLE 3.3

Case No.	Amplitudes A_1,A_2,A_3,A_4	Frequencies rad/sec $W_I \rightarrow$	Durations time, sec $t_I \rightarrow$	SRSS %	C/CC %	Phase angle
17	10,10,10	7.5,7.5,7.5	5,5,5	62	---	
18	10,10,10	7.5,7.5,7.5	5,4,3	52	---	
19	10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=7.5$ $\sigma_1=\sigma_2=\sigma_3=.5$	5,5,5	28	---	
20	10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=7.5$ $\sigma_1=\sigma_2=\sigma_3=.5$	5,4,3	22	---	
21	10,10,10,10	7.5,7.5,7.5,7.5	5,5,5,5	66	---	
22	10,10,10,10	7.5,7.5,7.5,7.5	5,4,3,2	51	---	
23	10,10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=W_{\mu_4}=7.5$ $\sigma_1=\sigma_2=\sigma_3=\sigma_4=.5$	5,5,5,5	35	---	
24	10,10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=W_{\mu_4}=7.5$ $\sigma_1=\sigma_2=\sigma_3=\sigma_4=.5$	5,4,3,2	35	---	

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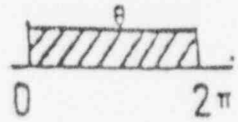
Combinations of Damped Sine Responses

TABLE 3.4

Case No.	Amplitudes A_1, A_2, A_3, A_4	Frequencies rad/sec $W_I \rightarrow$	Durations time, sec $t_I \rightarrow$	SRSS %	C/CC %	Phase angle
	Damped Responses					
25	10,10	7.5,7.5	5,5	55	2	
26	10,10	7.5,7.5	5,4	54	2	
27	10,10	$W_{\mu_1}=W_{\mu_2}=7.5$ $\sigma_1=\sigma_2=.5$	5,5	47	2	
28	10,10	$W_{\mu_1}=W_{\mu_2}=7.5$ $\sigma_1=\sigma_2=.5$	5,4	45	2	
29	10,10,10	7.5,7.5,7.5	5,5,5	62	2	
30	10,10,10	7.5,7.5,7.5	5,4,3	65	2	
31	10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=7.5$ $\sigma_1=\sigma_2=\sigma_3=.5$	5,5,5	57	2	
32	10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=7.5$ $\sigma_1=\sigma_2=\sigma_3=.5$	5,4,3	53	2	
33	10,10,10,10	7.5,7.5,7.5,7.5	5,5,5,5	67	2	
34	10,10,10,10	7.5,7.5,7.5,7.5	5,4,3,2	63	2	
35	10,10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=W_{\mu_4}=7.5$ $\sigma_1=\sigma_2=\sigma_3=\sigma_4=.5$	5,5,5,5	56	2	
36	10,10,10,10	$W_{\mu_1}=W_{\mu_2}=W_{\mu_3}=W_{\mu_4}=7.5$ $\sigma_1=\sigma_2=\sigma^3=\sigma_4=.5$	5,4,3,2	48	2	
37	10,10,10,10	$\sigma_1=\sigma_2=\sigma_3=\sigma_4=.4$	5,4,3,2	44	2	
38	10,10,10,10	$\sigma_1=\sigma_2=\sigma_3=\sigma_4=.2$	5,4,3,2	48	2	
39	10,10,10,10	$\sigma_1=\sigma_2=\sigma_3=\sigma_4=.1$	5,4,3,2	51	2	

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2. Two different frequencies are a primary factor in reducing the percent of non-exceedance,
3. Amplitude ratio is not a primary factor in changing the percent of non-exceedance,
4. Increased damping will raise percent of non-exceedance,
5. Density function for random phase angle is not a primary factor,
6. For random frequencies with normal distribution, an increase in σ lowers the percent of non-exceedance,
7. More of the same sine waves will raise the percent of non-exceedance.

3.7 Complex Sine Waves

Additional studies were made of two or more responses in which each response was composed of at least two sine waves. This was done because the amplitudes are fixed for the case of simple sine waves and the peaks occur periodically. With more than one sine wave, the shape of each response could be altered. The relative frequency content, numbers of peaks and amplitude configuration are easily changed and the effects of these changes on the response combination could be studied. In particular, simply by shifting the phase relationship between the components, the physical appearance of each response as plotted is different. The harmonic content is still the same but the magnitude and the appearance of the peaks changes with the phase shifting of the individual components.

Large changes in the NEP of SRSS were obtained by using this procedure. Relatively simple changes of a particular parameter in the equation which defined the sinusoidal components of a response gave very different results of non-exceedance percentages.

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Each separate complex response is defined as:

$$X_i(t) = \Sigma \; a_i \sin(\omega_i t + \varphi_i) \qquad (3.7.1)$$

the $X_i(t)$ are the separate responses, or signals, which are to be combined as:

$$R_i(t) = \Sigma X_i(t - t_D) \tag{3.7.2}$$

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to get a response combination.

Equation (3.7.1) is completely deterministic. The components are defined beforehand, including the phase angle φ_i. The combination $R_i(t)$, Equation (3.7.2), however, has a randomly distributed delay time, t_D, between the two response signals that are to be combined, in accordance with the procedures used in previous sections.

Four particular cases have been selected to show the concepts and conclusions that were developed in reference to the extension of sine waves into complex waves. All cases involve the combination of only two response signals. In the first two combinations, each of the two signals is composed of a fundamental sine wave and a third harmonic. In the third and fourth combination cases, each of the two response signals has four sinusoidal components.

The first signal used is described by

$$X_1(t) = 10 \sin 10t - 5 \sin 30t. \tag{3.7.3}$$

This is combined with an identical signal described by

$$X_2(t) = 10 \sin 10 (t - t_D) - 5 \sin 30 (t - t_D) \tag{3.7.4}$$

where the random delay time, t_D, is used in the combination. Previous studies in Section 3.2 had shown that the distribution of the random delay time was not of primary importance in the maximum response, $R_i(t)$ where

$$R_i(t) = X_1(t) + X_2(t - t_D). \tag{3.7.5}$$

A uniform distribution of t_D was taken over an interval equal to the period of the longest component of the first signal.

Figure 3.8 shows a plot of Equation (3.7.3). The result of the combination of Equations (3.7.3) and (3.7.4) gave an NEP of SRSS of 72 percent. This

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P(R<SRSS) @ 72%

$X(\tau) = 10 \sin 10\tau - 5 \sin 30\tau$

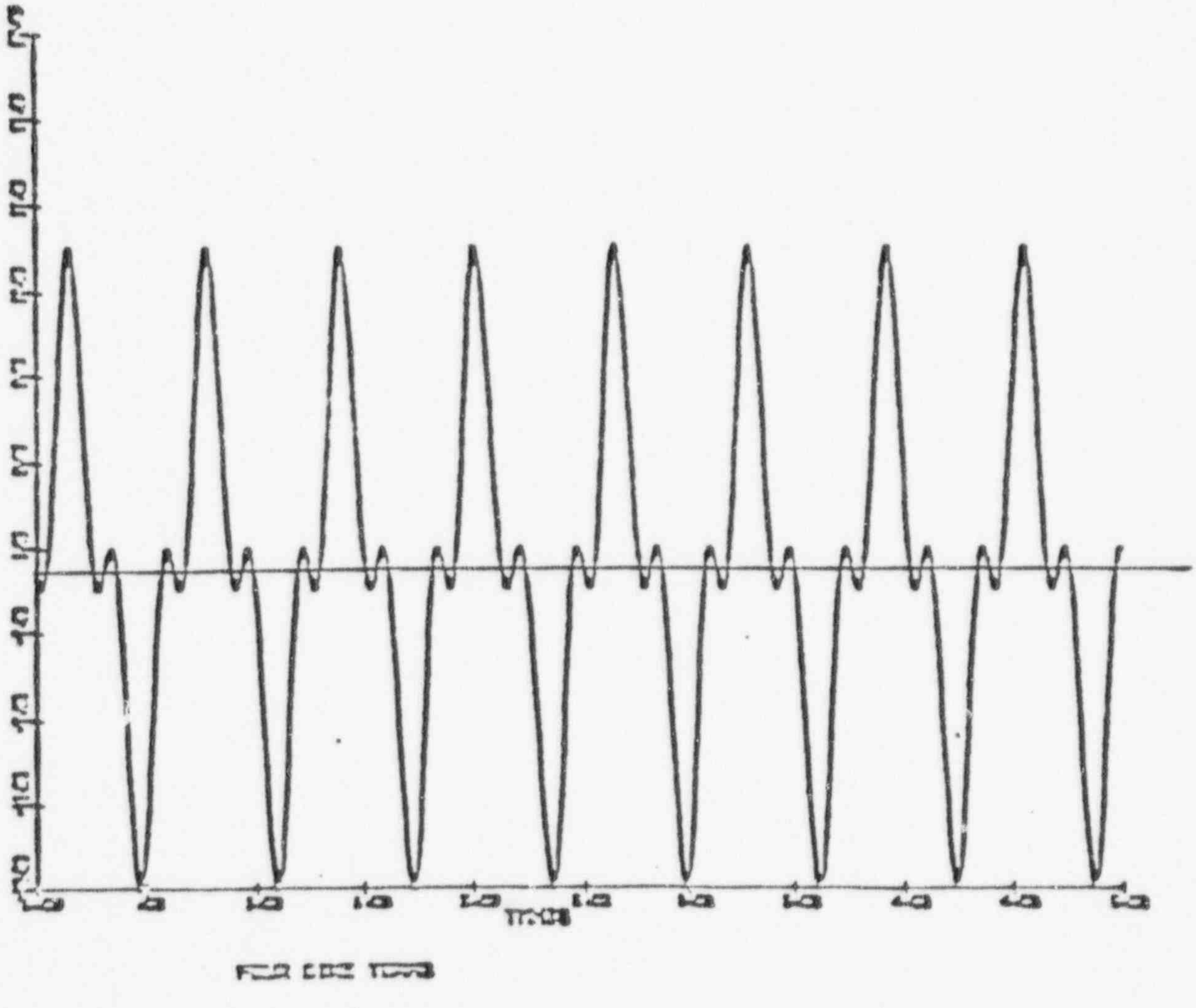

Fig. 3.8 Response $X_I(T)$, Combined Randomly With Itself.

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is much higher than the 50% for the random combination of two identical, single-term sine waves.

The second case uses the same sinusoidal components as in the first case, but substitutes a phase change for the third harmonic component. A plus sign is used instead of the minus sign. The equation for Case 2 is

$$X_1(t) = 10 \sin 10t + 5 \sin 30t \tag{3.7.6}$$

$$X_2(t) = 10 \sin 10(t - t_d) + 5 \sin 30(t - t_d) \tag{3.7.7}$$

Figure 3.9 shows the plot of the response signal used for the second case. The NEP of SRSS this time is reduced to only 28%.

For both, cases one and two, the same frequency components are involved in each response signal. Only a deterministic phase change was used in the components of a signal. The appearance of the signals is greatly changed. If a line is drawn at a level of 50 percent of the maximum, both signals in Figures 3.8 and 3.9 have the same number of peaks. However, in the first case, the peak is narrow while in the second case the peak is broad. This difference in width has made it more probable for combinations using a random time delay to exceed the SRSS valve, hence the NEP of SRSS is reduced from 72% to 28%. As the wave becomes broader, the NEP of SRSS can be expected to decrease further.

So far, the response signals were regular in form and repeated themselves every cycle. They did not look "earthquake like", as would the kind of responses from an SSE. Therefore, the third and fourth cases use sine waves to produce complex waves that are not periodic in the interval of interest. The peaks do not repeat every cycle and are not evenly spaced. Four sinusoidal components are used to do this. In particular, the response signal is taken of the form:

$$X_1(t) = 10 \sin 4.375t + 10 \sin 10t + 10 \sin 30t + 20 \sin 30t \tag{3.7.8}$$

A plot of Equation (3.7.8) is shown in Figure 3.10. It is seen that the wave

P(R<SRSS) @ 28%

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$X_2(\tau) = 10 \sin 10\tau + 5 \sin 30\tau$

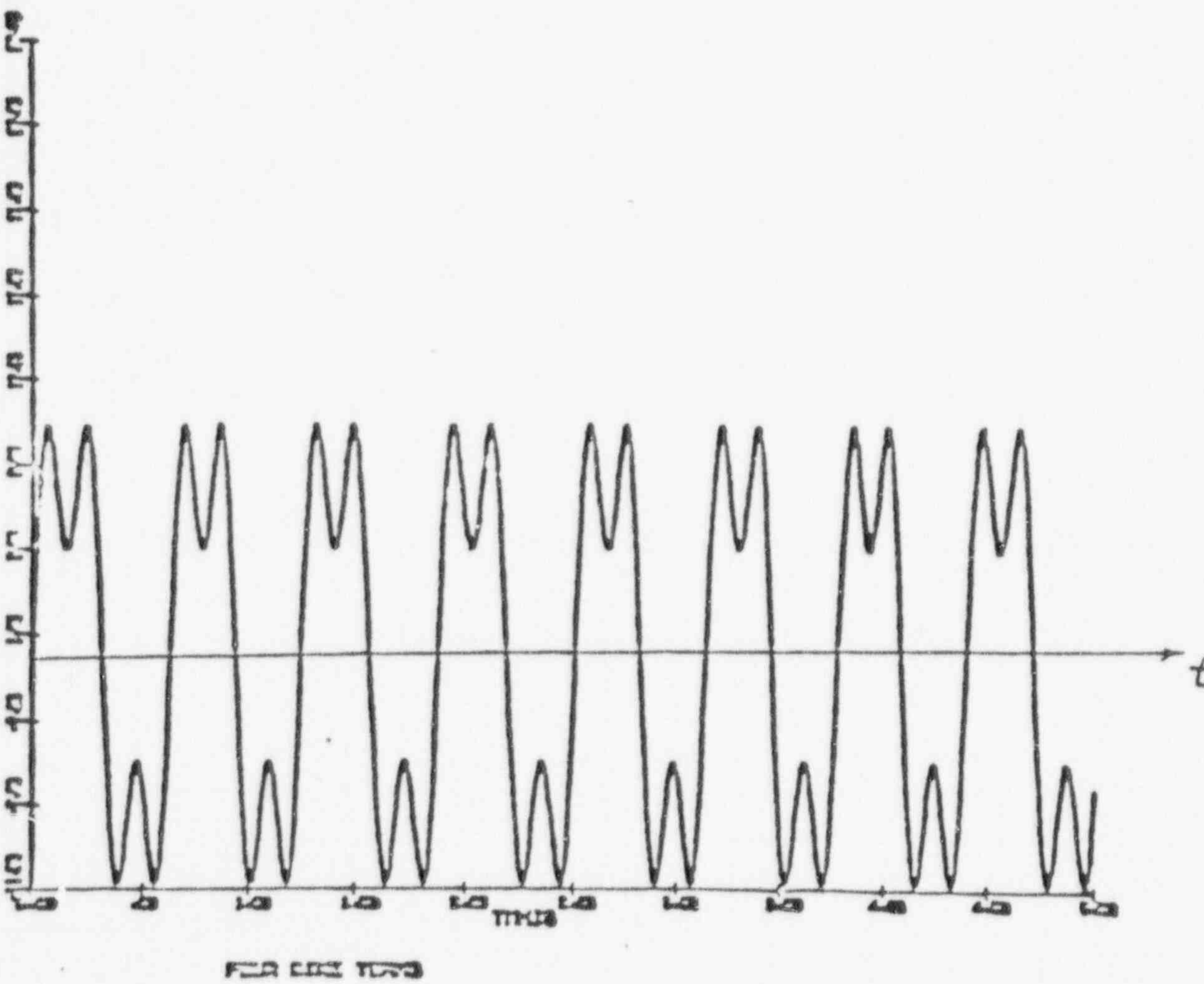

Fig. 3.9 Response $X_2(T)$ Combined With X(T) From Fig. 3.8

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P(R<SRSS) @ 72%

$$X_1(T) = 10 \sin 4.375T + 10 \sin 10T - 10 \sin 20T + 20 \sin 30T$$

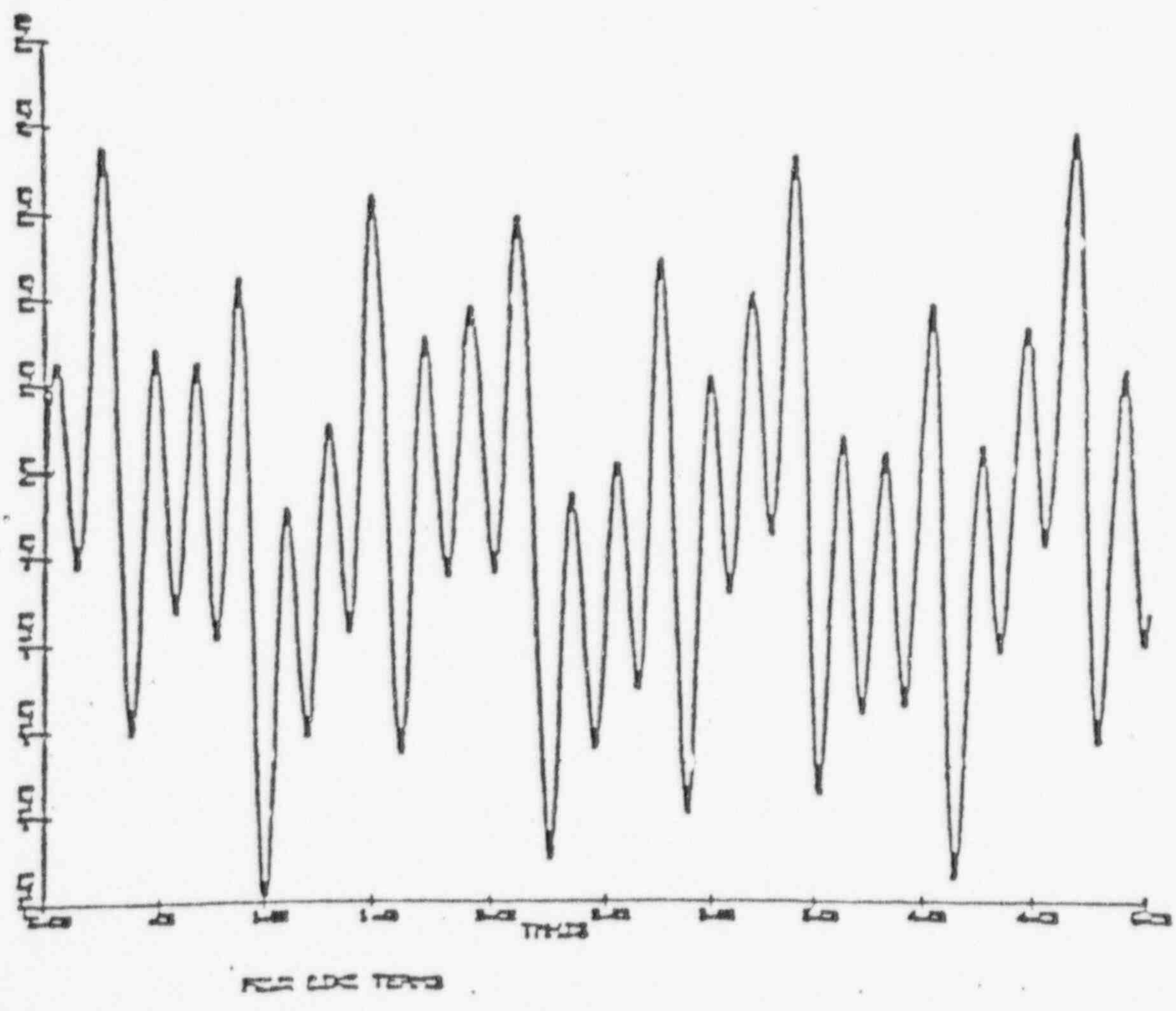

Fig. 3.10 Form Sine Terms, Reponse $X_1(T)$ Combined Randomly With Itself

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does not repeat itself during the five seconds of its occurrence. The peaks are not repetitive and there are few peaks. For the upper part of the signal, there are 5 peaks greater than 75 percent of maximum and 8 greater than 60 percent while for the lower part, these numbers are 3 and 5, respectively. The wave has an "earthquake like " appearance.

For the third case, Equation (3.7.8) was combined with an identical signal and with uniformly distributed random delay time. The resulting NEP of SRSS is at 72 percent. This means that the use of SRSS is conservative in that it is unlikely that the peaks would combine (72% of the cases have SRSS greater than the peak combined response).

For the fourth case, a signal with the same complexity of the third case was selected. However, the frequency components were all doubled. For this response combination, the second response signal was:

$$X_2(t) = 10 \sin 8.75t + 10 \sin 20t - 10 \sin 40t - 20 \sin 60t \qquad (3.7.9)$$

Equation (3.7.9) was then combined with Equation (3.7.8) using uniform random distribution of the delay time. The Monte Carlo result for this combination gave an NEP of SRSS of only 13%. This is shown in Figure 3.11

There appears to be two reasons for this change. The first reason is that more peaks are developed by doubling the frequency. The second reason is that the occurrence of the peaks is not uniformly spaced. This provides many more opportunities for peaks of significant magnitude to combine. Thus, the NEP of SRSS is considerably reduced.

For Multisinusoidal Response the following additional conclusions may be drawn for assisting in the understanding of the maximum response of the combination of two signals.

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P(R<SRSS) @ 13%
WITH $X_1(T)$

$$X_2(T) = 10 \sin 8.75T + 10 \sin 20T - 10 \sin 40T + 20 \sin 60T$$

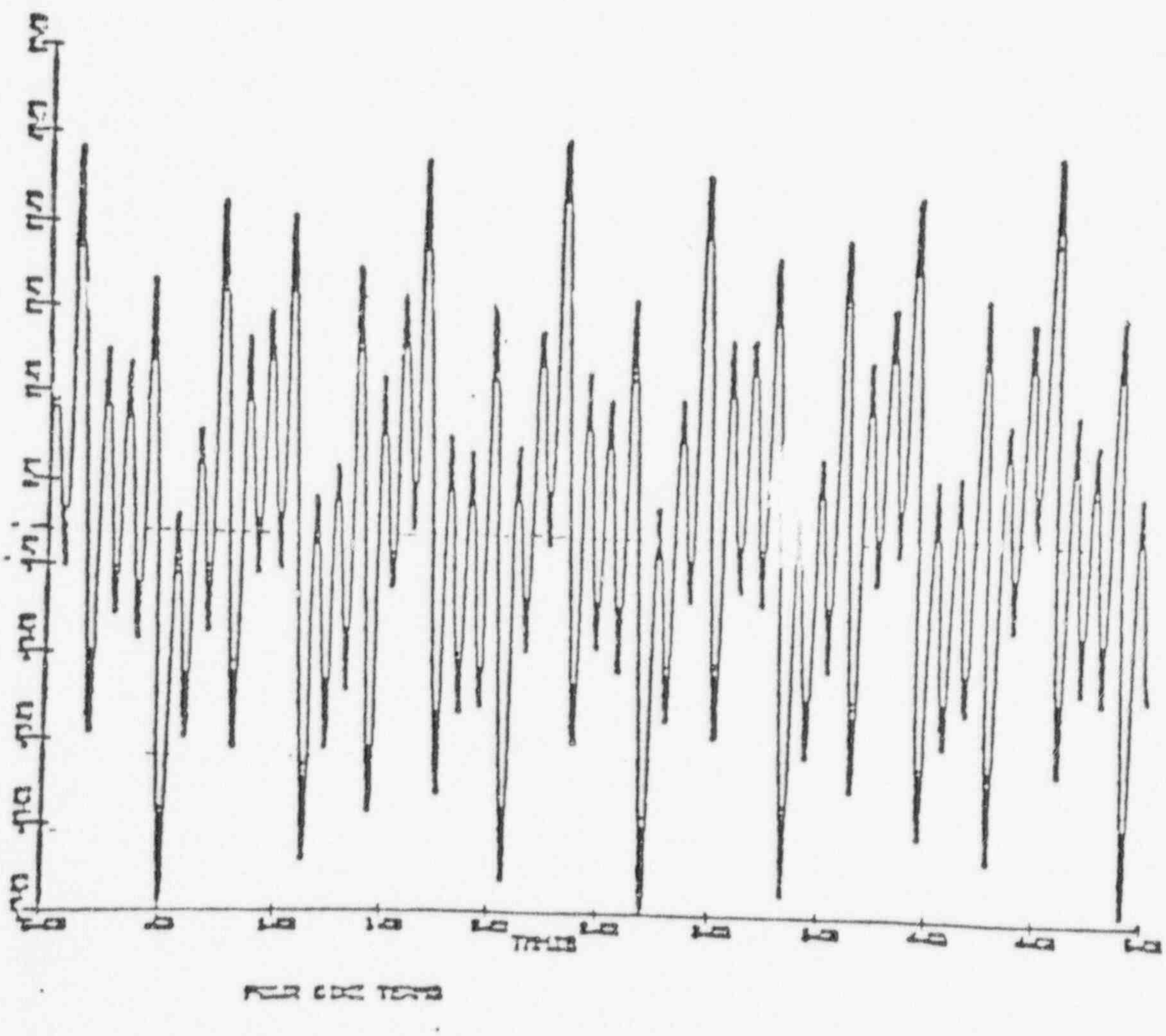

Fig. 3.11 Form Sine Term, Response $X_2(T)$, Combined Randomly With $X_1(T)$ q Fig. 3.10

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FOR MULTISINUSOIDAL RESPONSES

3.8 Conclusions

1. Frequency relations of major components will affect percent of non-exceedance, as is indicated in conclusions for sine response.
2. Number of peaks primary factor in determining percent of non-exceedance.
3. Reponses with same components can give very different percent of non-exceedance depending on phase angle of components.

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IV. COMBINATION OF ARTIFICIAL RESPONSE IN FREQUENCY DOMAIN

4.1 Purpose

As indicated in the previous discussions pertaining to the basic study of combining sinusoidal responses, the NEP of SRSS depends heavily on the frequency differences of the component responses. For real responses, the Fourier spectrum generally shows many frequency components with a relatively narrow band. Therefore, in order to study the effect of frequency contents, band width distribution as well as relative locations of predominant frequencies, needs to be considered. Artificial responses had to be generated in such a manner that parameter studies of the above mentioned effects could be carried out.

4.2 Method of Generating Responses in Frequency Domain

Any time dependent function can be represented by an infinite Fourier series:

$$R(t) = \sum_{k=0}^{\infty} \left(a_k \cos k\omega_o t + b_k \sin k\omega_o t\right)$$

$$= \sum_{k=0}^{\infty} C_k \cos(k\omega_o t - \phi_k) \tag{4.2.1}$$

For practical application, the digitization of the frequencies is limited from k = 1 to N, where N is a reasonably large number so that the time function can be properly reproduced. In the present case, for a time duration of ten seconds, N was set to 400. C_k is the normally distributed random amplitude with the predominant frequency as the mean and is given by the following expression:

$$C_k = A_k \, e^{-(k\omega_o - \mu_\omega)/2\sigma_\omega^{\,2}} \tag{4.2.2}$$

where A_k is a random number between 0 and the maximum Fourier amplitude, ω_o is the digitized frequency step, μ_ω is the predominant frequency, and σ_ω is

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the standard deviation of the frequency distribution. ϕ_k is the random phase angle.

A sample artificial response in the frequency domain is generated according to Equation (4.2.1) with preassigned values of the duration, the maximum Fourier amplitude, number of digitizations N, the predominent frequency μ_{ω}. The Fourier spectrum thus produced is then inverse transformed to the time domain. As required, two or more such sample signals can be generated. Once this is accomplished, the Monte Carlo simulation is carried out based on a random time lag of the component signals. Finally for each set of the combination, the CDF curve and the NEP of the SRSS is obtained and exhibited graphically. A schematic sequence of the particular steps in this process is shown in Figure 4.1. Typical generated signals are shown at the end of this section and in Appendix C.

4.3 Summary of Results

A summary of the results of combining artificial responses produced in the frequency domain is given in Table 4.1. These results are classified into cases according to the mean frequencies, frequency deviations, and the durations. The NEP of SRSS is given in the next to the last column of the table. A new parameter denoted as the ratio of σ to R_{max} is also introduced in table 4.1. The definition of σ is the standard deviation of the peak values, of individual response, i.e.

$$\sigma = \left(\frac{\Sigma R^2}{N}\right)^{\frac{1}{2}}$$

and R_{max} is the maximum absolute value of the peaks. When different responses are combined, the parameter $\dfrac{\sigma}{R_{max}}$ is determined as follows

$$\frac{\sigma}{R_{max}} = \sqrt{\Sigma \frac{\sigma_i}{R_{imax}}^2}$$

This latter quantity is shown concurrently when two different responses are combined. As will be discussed in the subsequent sections, the parameter

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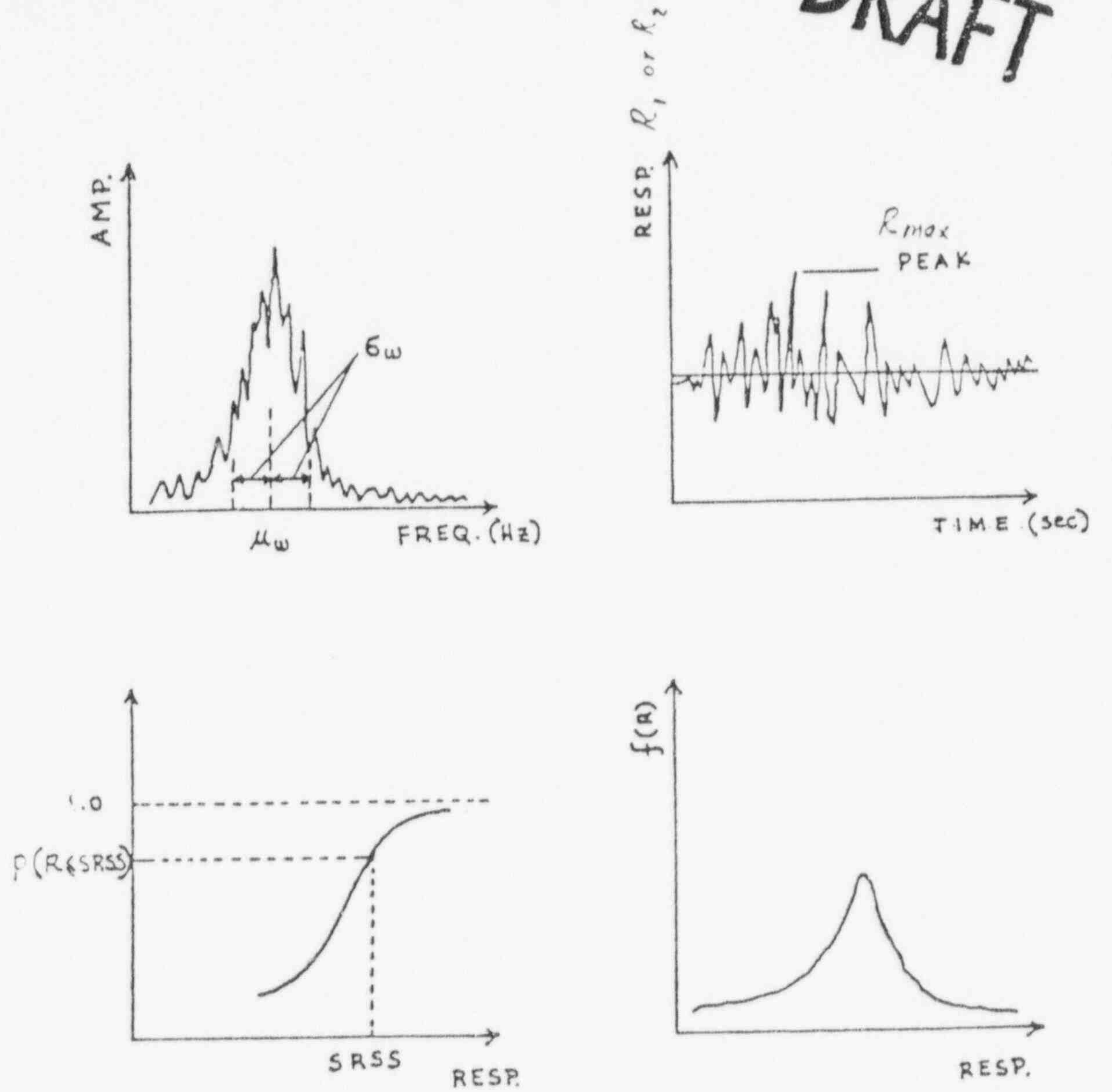

CUMULATIVE DENSITY FUNCTION. (CDF).

DENSITY FUNCTION. (DF).

RESULTS : $R(t) = R_1(t) + R_2(t+\tau)$

τ is random time.

Fig. 4.1

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TABLE 4.1

Summary of Results for Combining Two Responses Produced in Frequency Domain

Comb. No.	Comb. No.	CENT. FREQ (rps)	FREQ DEV (rps)	Dur. (sec.)	No. of Peaks > 75% max	No. of Peaks > 60% max	$\frac{\sigma}{R_{max}}$	Prob.(R_{comb} < SRSS)
1	1 2	8 8	1 1	10 10	7 7	20 20	.325	.88
2	1 2	8 8	3 3	10 10	8 8	24 24	.324	.81
3	1 2	8 8	5 5	10 10	7 7	22 22	.319	.75
4	1 2	6 6	1 1	10 10	8 8	18 18	.281	.91
5	1 2	6 6	3 3	10 10	11 11	23 23	.321	.78
6	1 2	6 6	5 5	10 10	6 6	23 23	.321	.78
7	1 2	8 8	1 1	10 5	7 9	20 28	.325 .352 .378	.81
8	1 2	8 8	3 3	10 5	8 8	24 24	.323 .350 .376	.67
9	1 2	8 8	5 5	10 5	7 13	22 24	.319 .358 .394	.62
10	1 2	6 6	1 1	10 5	8 8	18 18	.280 .288 .296	.88
11	1 2	6 6	3 3	10 5	11 9	13 21	.319 .343 .366	.68
12	1 2	6 6	5 5	10 5	6 11	23 22	.321 .351 .379	.64
13	1 2	6 12	1 1	10 10	8 15	18 36	.281 .317 .350	.59
14	1 2	6 12	3 3	10 10	11 4	23 20	.321 .318 .315	.77
15	1 2	6 12	5 5	10 10	6 13	23 36	.321 .342 .362	.68
16	1 2	4 12	1 1	10 10	15 15	57 36	.376 .363 .350	.62

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TABLE 4.1-Continued

Summary of Results for Combining Two Responses Produced in Frequency Domain

Comb. No.	Comb. No.	CENT. FREQ (rps)	FREQ DEV (rps)	Dur. (sec.)	No. of Peaks > 75% max	No. of Peaks > 60% max	$\frac{\sigma}{R_{max}}$	Prob.(R_{comb} < SRSS)
	1	4	3	10	15	44	.359	
17							.338	.76
	2	12	3	10	4	20	.315	
	1	4	5	10	8	27	.329	
18							.346	.68
	2	12	5	10	13	36	.362	
	1	6	1	10	8	18	.281	
19							.289	.78
	2	12	1	5	5	10	.279	
	1	6	3	10	11	23	.321	
20							.302	.81
	2	12	3	5	3	8	.282	
	1	6	5	10	6	23	.321	
21							.305	.84
	2	12	5	5	3	6	.289	
	1	4	1	10	15	57	.376	
22							.339	.69
	2	12	1	5	5	10	.297	

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$\frac{\sigma}{R_{max}}$ appears to play an important role in the combination result.

4.4 Conclusions

According to the results, the following conclusions can be drawn with regard to the combination of artificial responses generated in the frequency domain:

1. NEP of SRSS decreases with increasing frequency bandwidth when predominant frequencies are same,
2. NEP of SRSS increases somewhat with smaller predominant frequencies,
3. NEP of SRSS decreases when predominant frequency differences increases,
4. NEP of SRSS may increase or decreases when the second response decreases in duration,
5. When both frequency and dufation differences occur, it is shown in Section VI. that NEP of SRSS may reach .30 to .40.

4.5 Sample Combination of Dynamic Response in Frequency Domain

Some cases described in Table 4.1 are shown in the subsequent figures. In particular, the graphical plots for combination cases 3,9,16, and 22 are given in figures 4.2-4.6. For each of the cases the Fourier Spectrum, is shown first with the corresponding time history shown beneath. For the case of identical responses, this in followed by the CDF curve ~~is~~ and the corresponding probability density curve. Where two different responses are combined the Fourier Spectrum and time history for each response is also shown.

Case A-3: Identical Responses. (Comb. No. 3)

ω = 8 rps
σ_{ω} = 5 rps
Dur = 10 rps

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Case B-3: Two Reponses with Different Duration. (Comb. No. 9)

ω = 4 rps
σ_ω = 5 rps
Dur(1) = 10 sec
Dur(2) = 5 sec

Case C-1: Two Responses with Different Cent. Freq. and Same Duration. (Comb. No. 13)

ω_1 = 6 rps
ω_2 = 12 rps
σ_ω = 1 rps
Dur = 10 sec.

Case C-4: Two Responses with Different Cent. Freq. and Same Duration. (Comb. No. 16)

ω_1 = 4 rps
ω_2 = 12 rps
σ_ω = 1 rps
Dur(1) = 10 sec.

Case D-4: Two Responses with Different Cent. Freq. and Different Durations. (Comb. No. 22)

ω_1 = 4 rps
ω_2 = 12 rps
σ_ω = 5 rps
Dur(1) = 10 sec.
Dur(2) = 5 sec.

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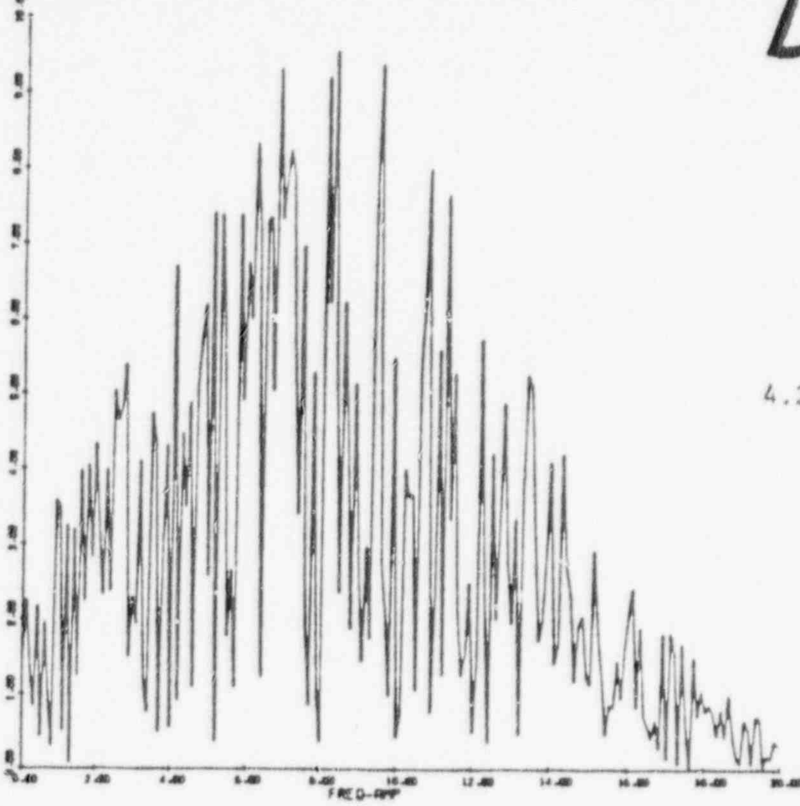
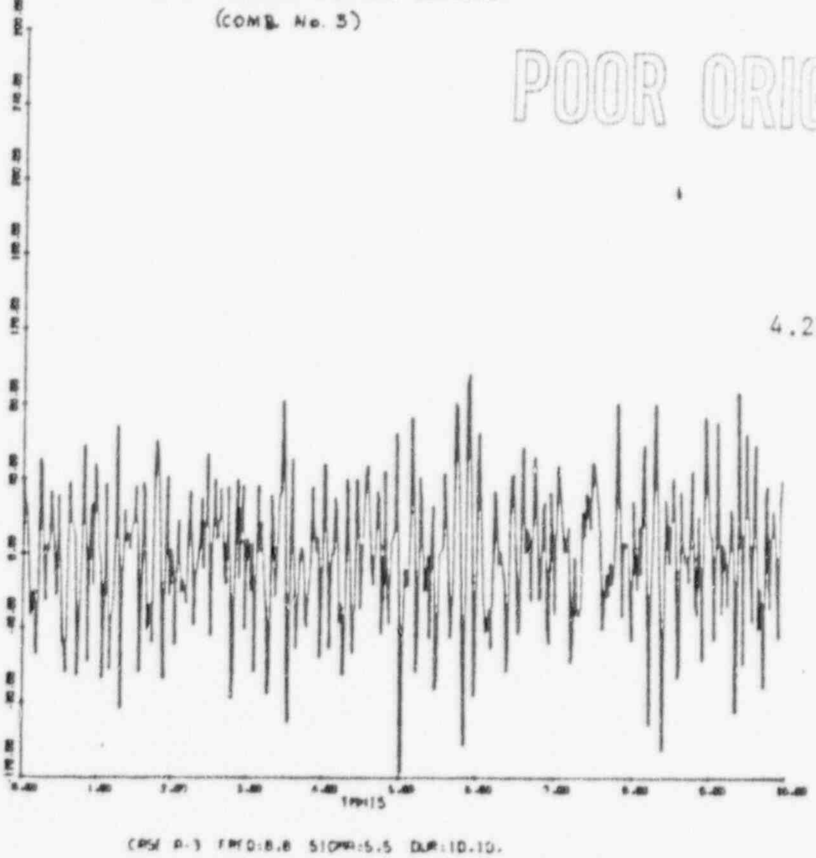


4.2a

CASE A-3 FREQ=8.8 SIGMA=5.5 DUR=10.10.

(COMB. No. 5)

POOR ORIGINAL



4.2b

CASE A-3 FREQ=8.8 SIGMA=5.5 DUR=10.10.

(COMB. No. 5)

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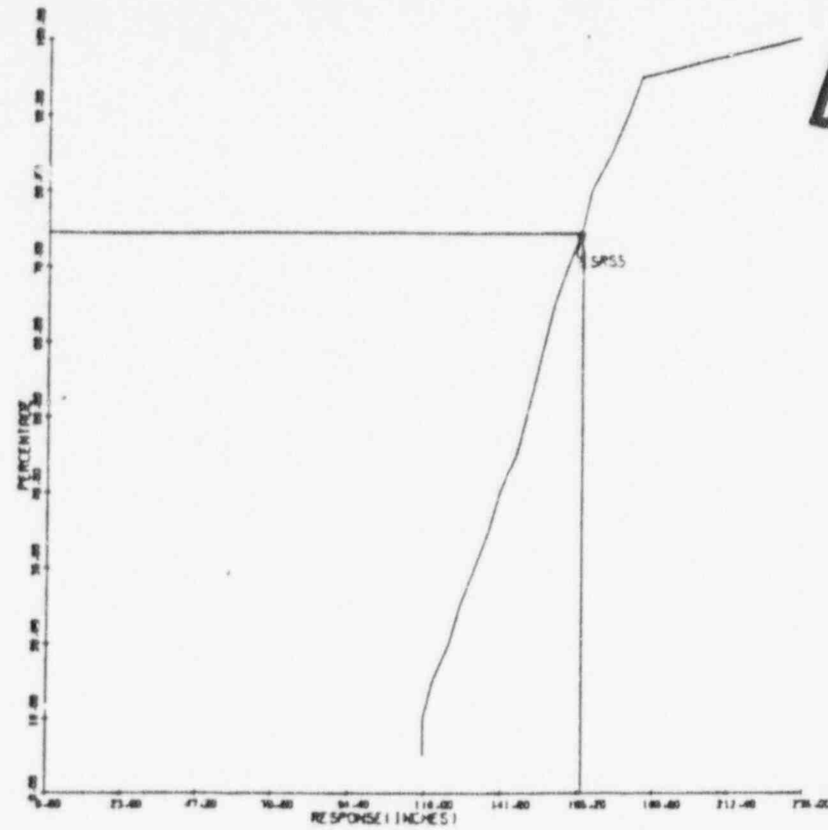
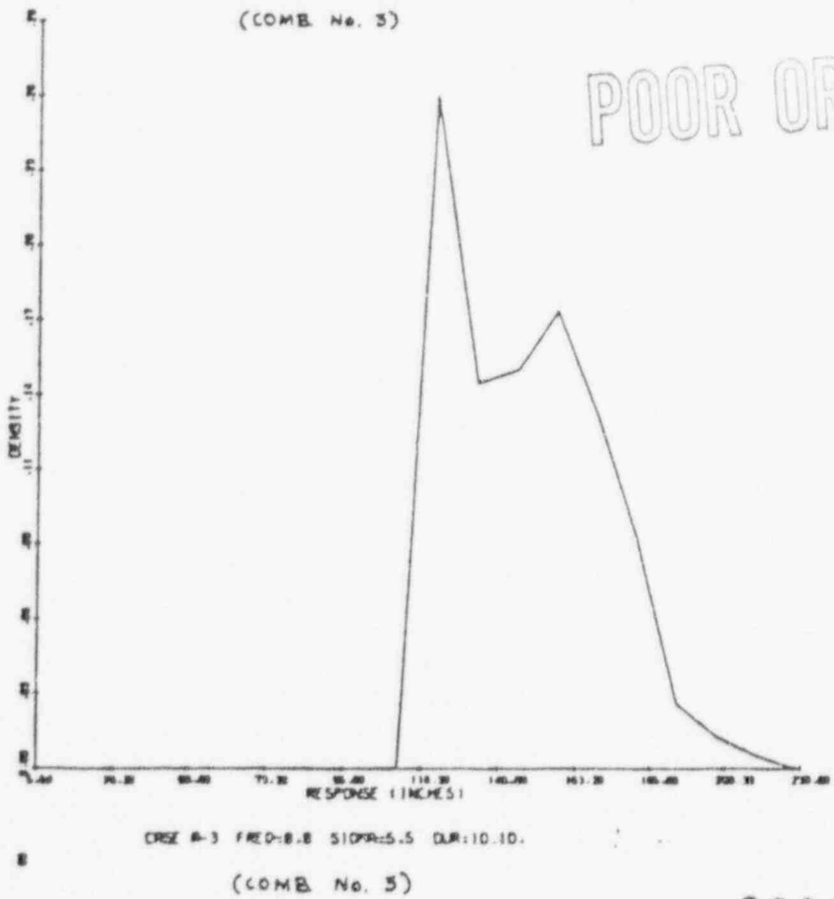


4.2c

CASE A-3 FREQ=8.8 SIGMA=5.5 DUR=10.10.

(COMB. No. 3)

POOR ORIGINAL



4.2d

CASE A-3 FREQ=8.8 SIGMA=5.5 DUR=10.10.

(COMB. No. 3)

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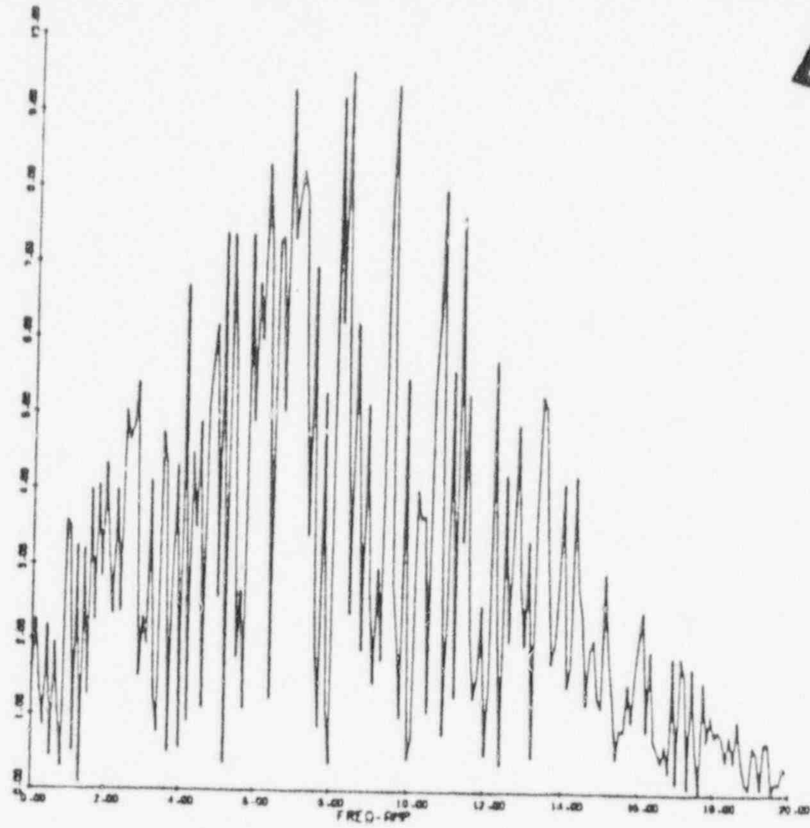
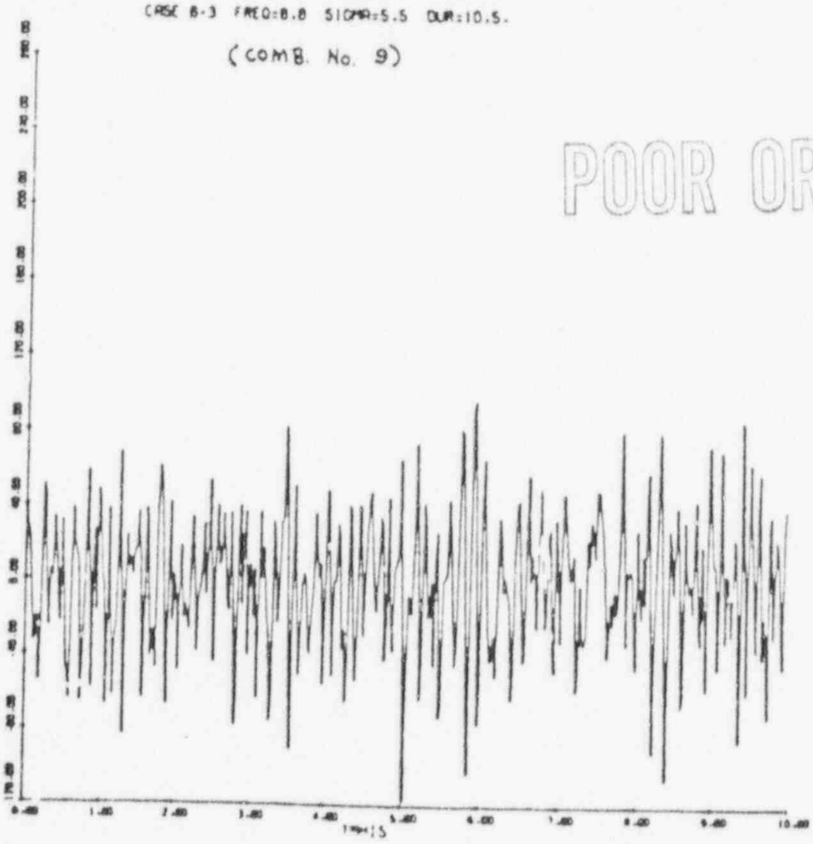


4.3a

CASE B-3 FREQ:8.8 SIGMA=5.5 DUR:10.5.

(COMB. No. 9)

POOR ORIGINAL



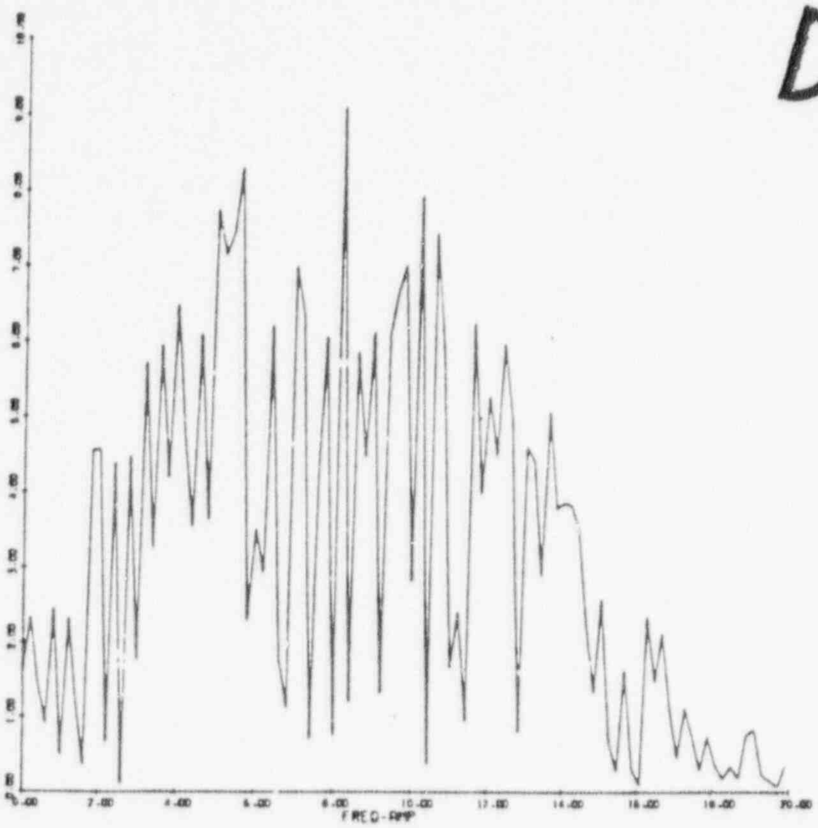
4.3b

CASE B-3 FREQ:8.8 SIGMA:5.5 DUR:10.5.

(COMB. No. 9)

90011056

DRAFT

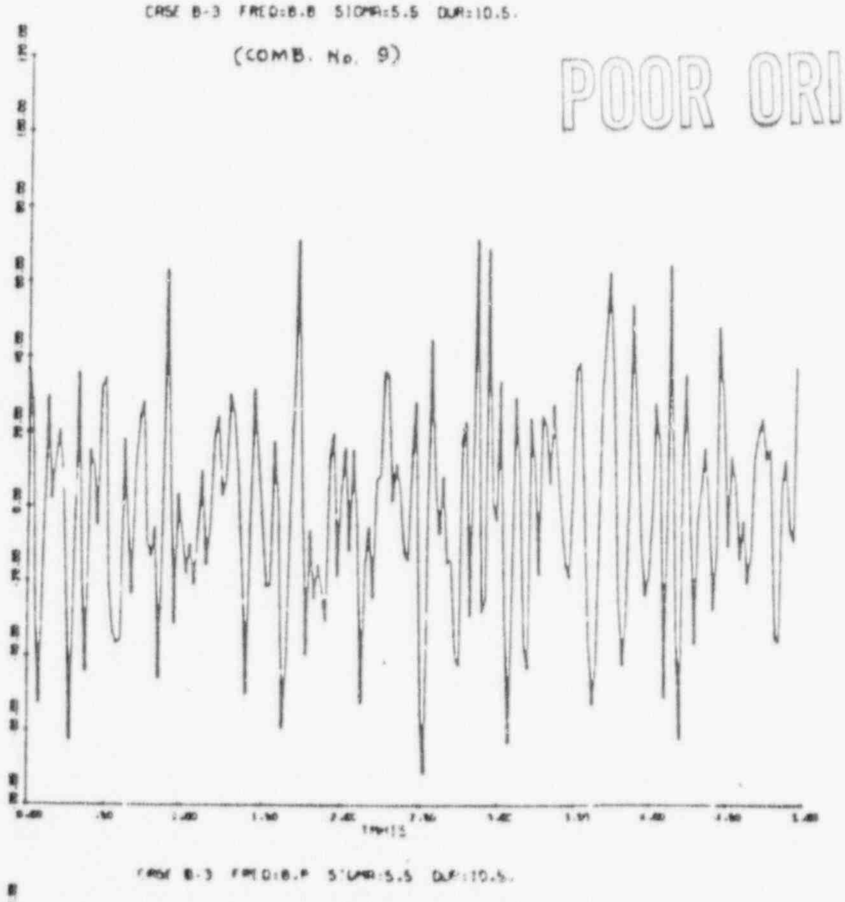


4.3c

CASE B-3 FREQ:8.8 SIGMA:5.5 DUR:10.5.

(COMB. No. 9)

POOR ORIGINAL

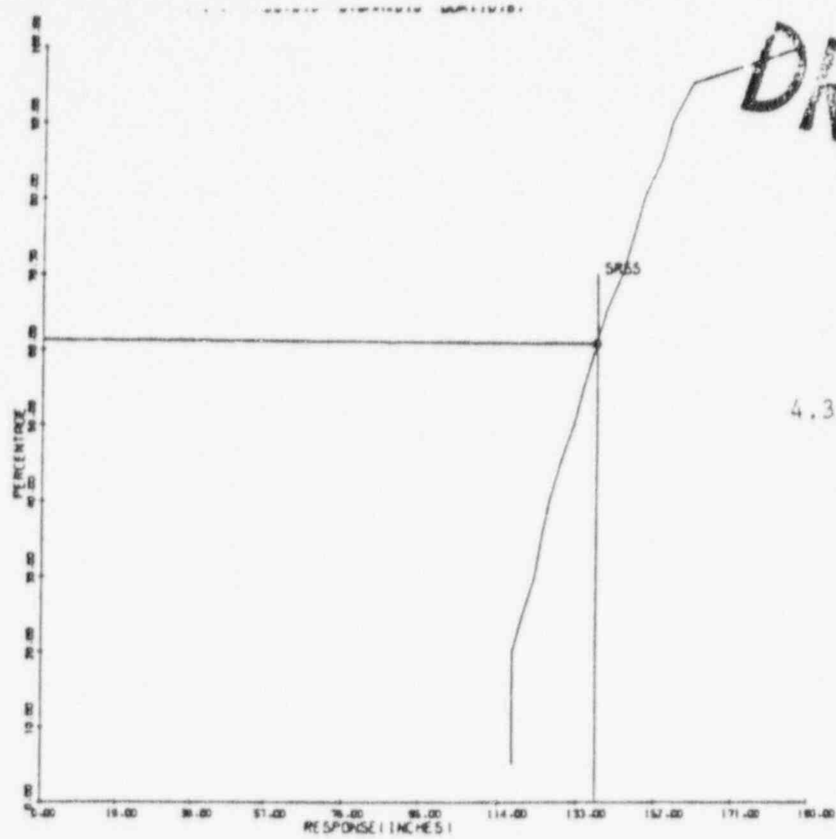


4.3d

CASE B-3 FREQ:8.8 SIGMA:5.5 DUR:10.5.

(COMB. No. 9)

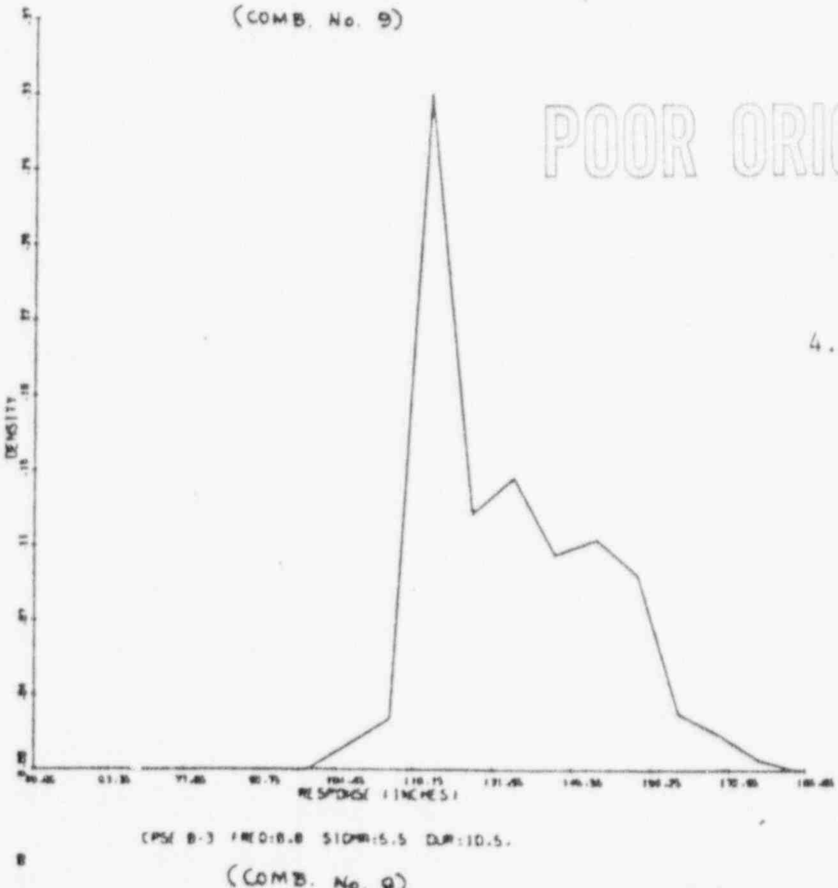
90011057



4.3e

CASE B-3 FREQ:8.8 SIGMA:5.5 DUR:10.5.

(COMB. No. 9)



4.3f

CASE B-3 FREQ:8.8 SIGMA:5.5 DUR:10.5.

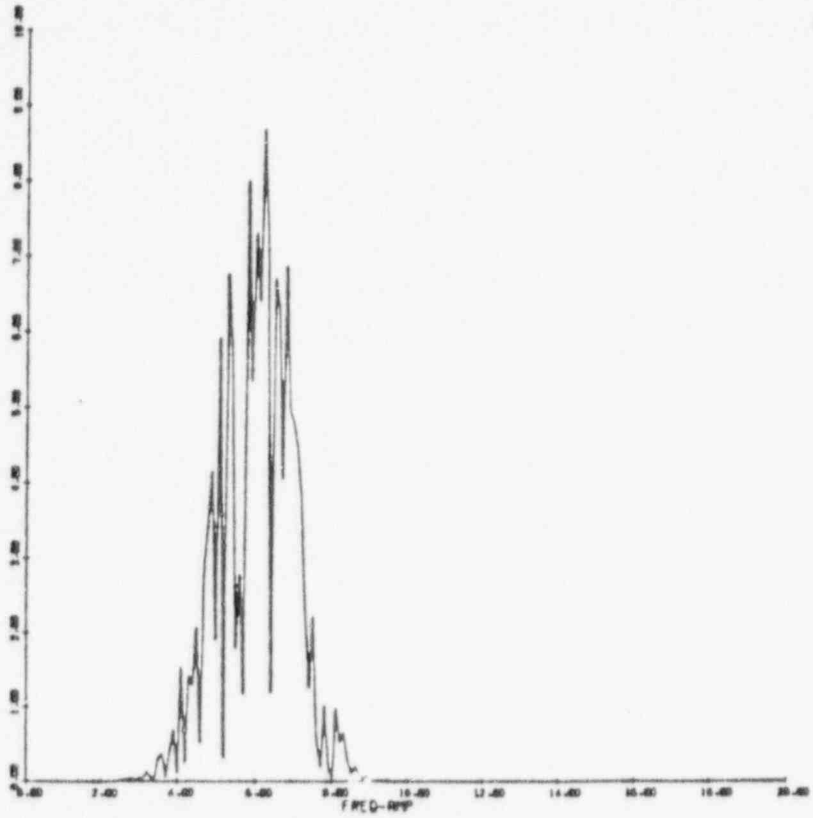
(COMB. No. 9)

DRAFT

POOR ORIGINAL

90011058

DRAFT

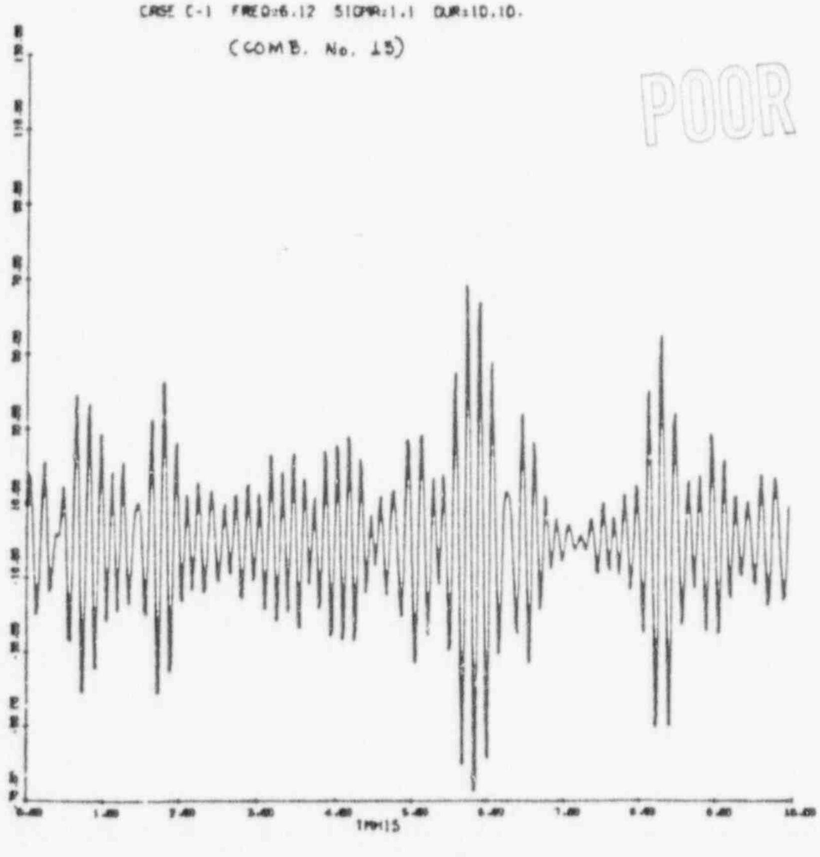


4.4a

CASE C-1 FREQ=6.12 SIGMA=1.1 DUR=10.10.

(COMB. No. 15)

POOR ORIGINAL



4.4b

CASE C-1 FREQ=6.12 SIGMA=1.1 DUR=10.10.

(COMB. No. 15)

90011059

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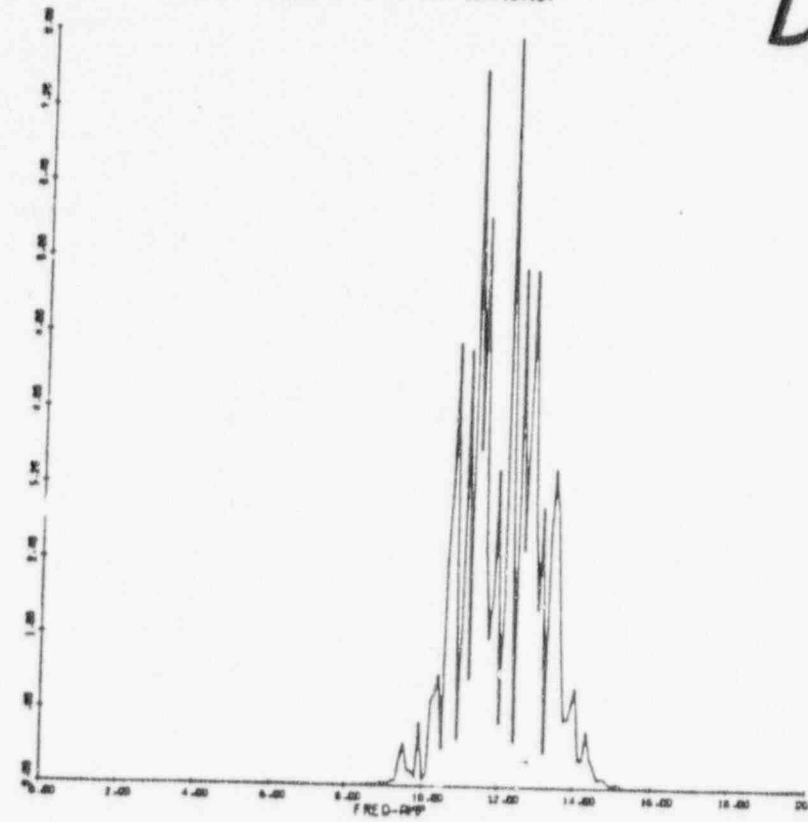
CASE C-1 FREQ=6.12 SIGMA=1.1 DUR=10.10.

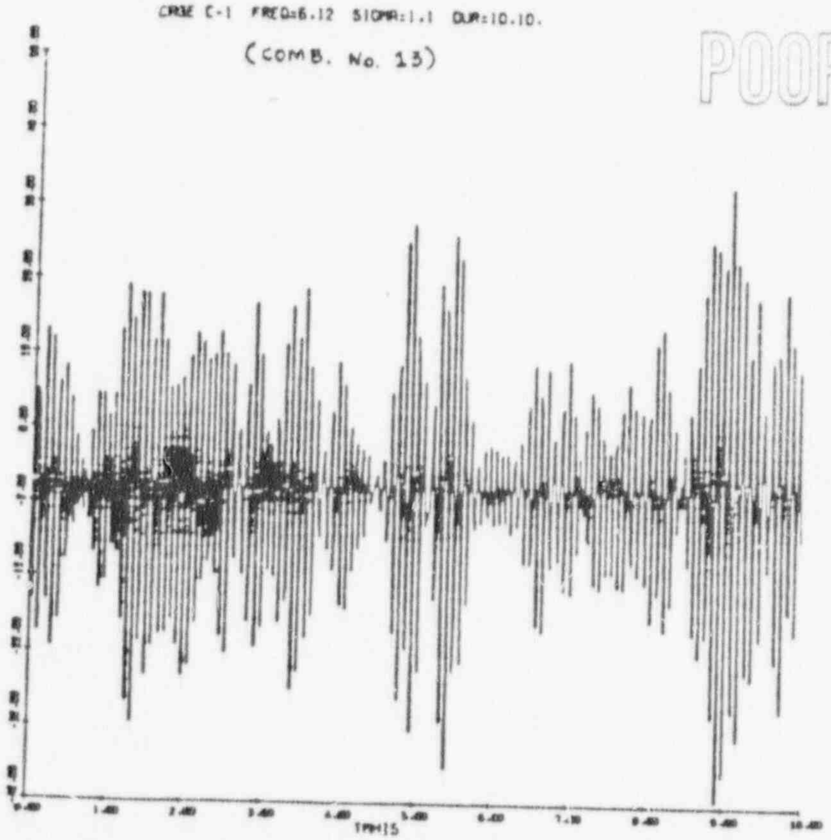


4.4c

CASE C-1 FREQ=6.12 SIGMA=1.1 DUR=10.10.

(COMB. No. 13)

POOR ORIGINAL



4.4d

CASE C-1 FREQ=6.12 SIGMA=1.1 DUR=10.10.

(COMB. No. 13)

90011060

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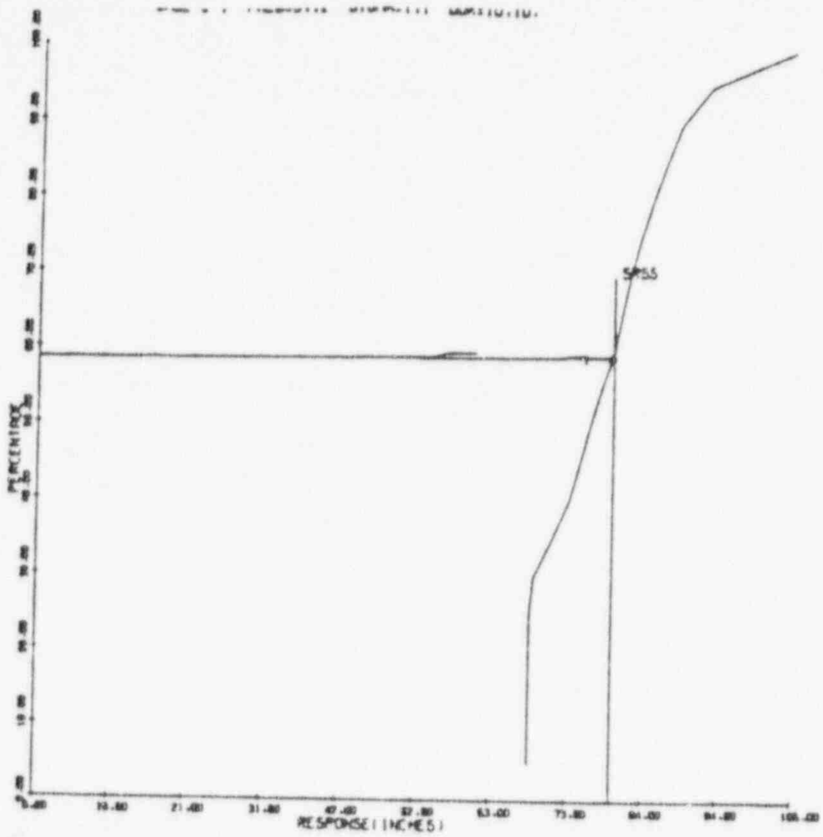
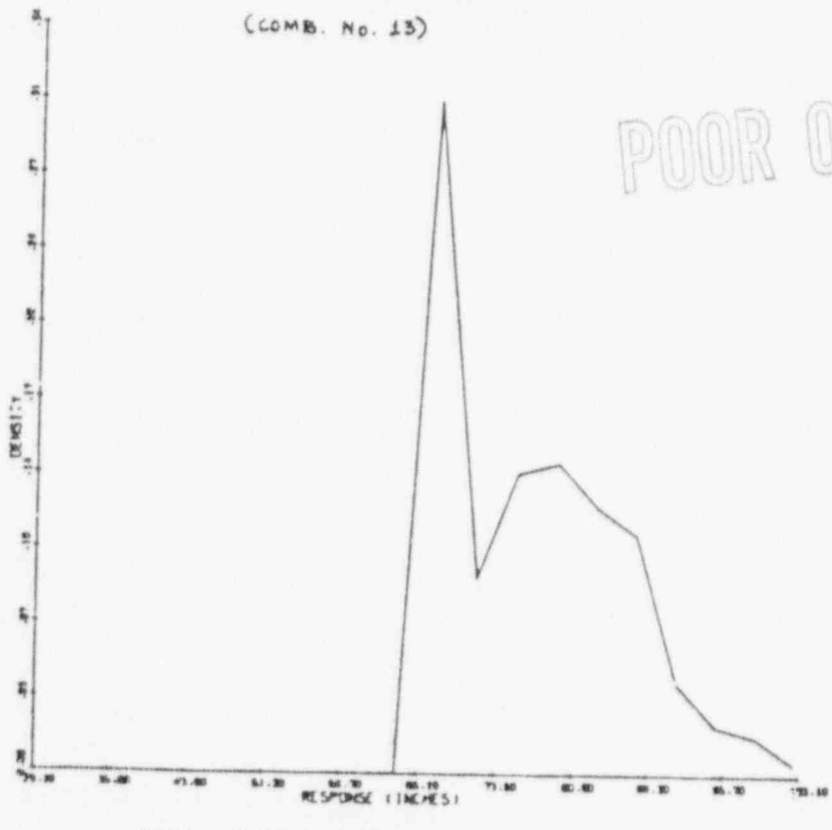


CASE C-1 FREQ:6.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 13)

4.4e



POOR ORIGINAL

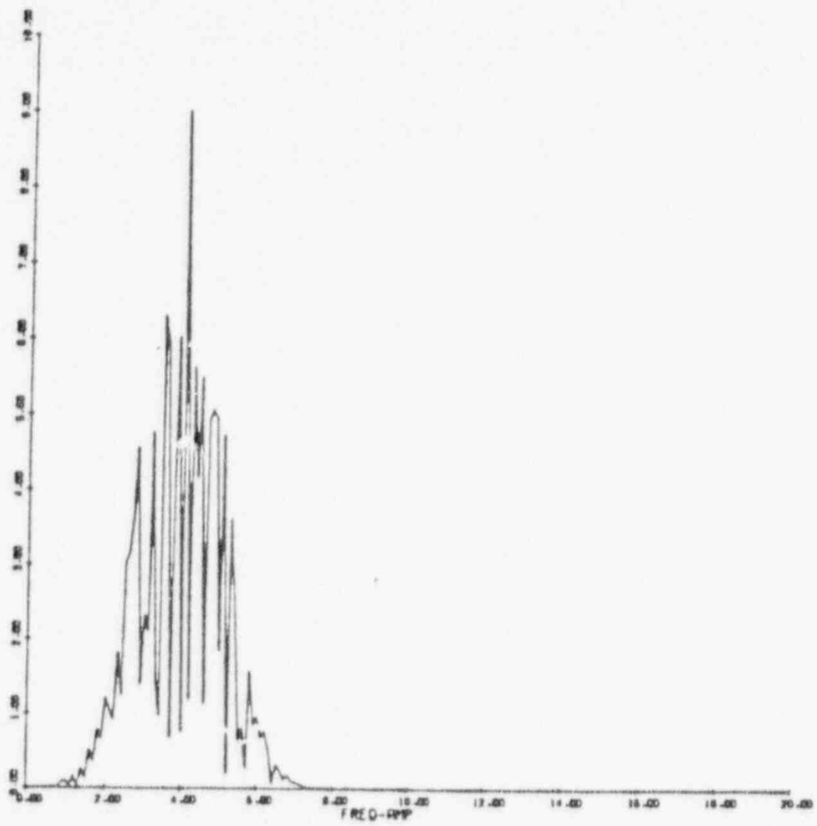
4.4f

CASE C-1 FREQ:6.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 13)

90011061

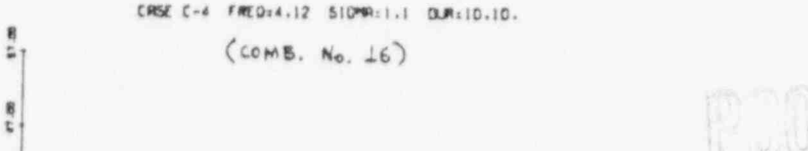
DRAFT



4.5a

CASE C-4 FREQ:4.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 16)



4.5b

CASE C-4 FREQ:4.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 16)

90011062

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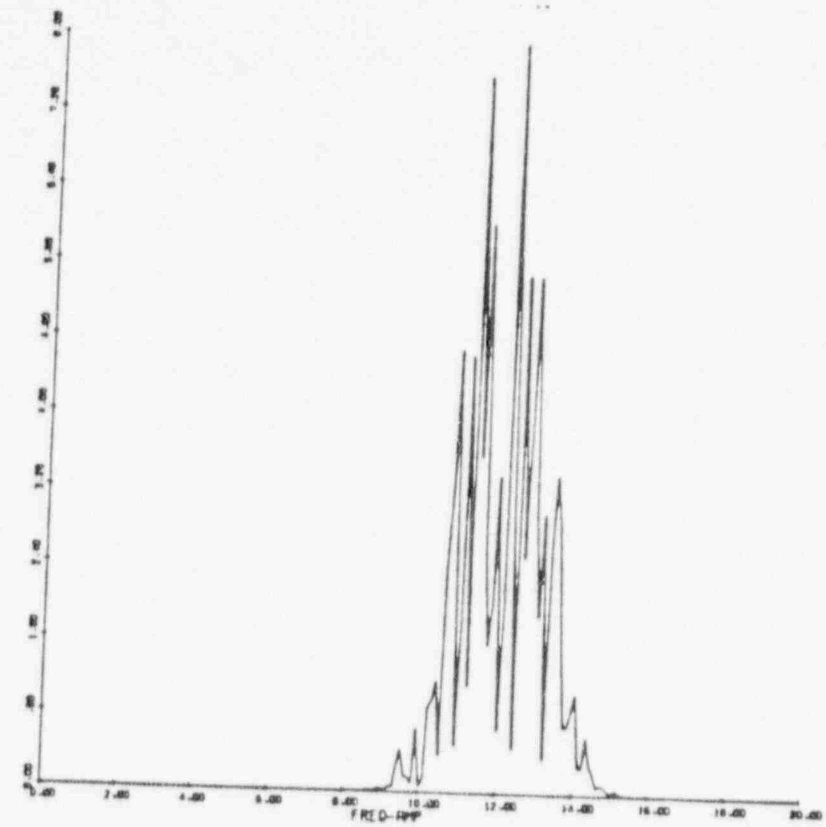
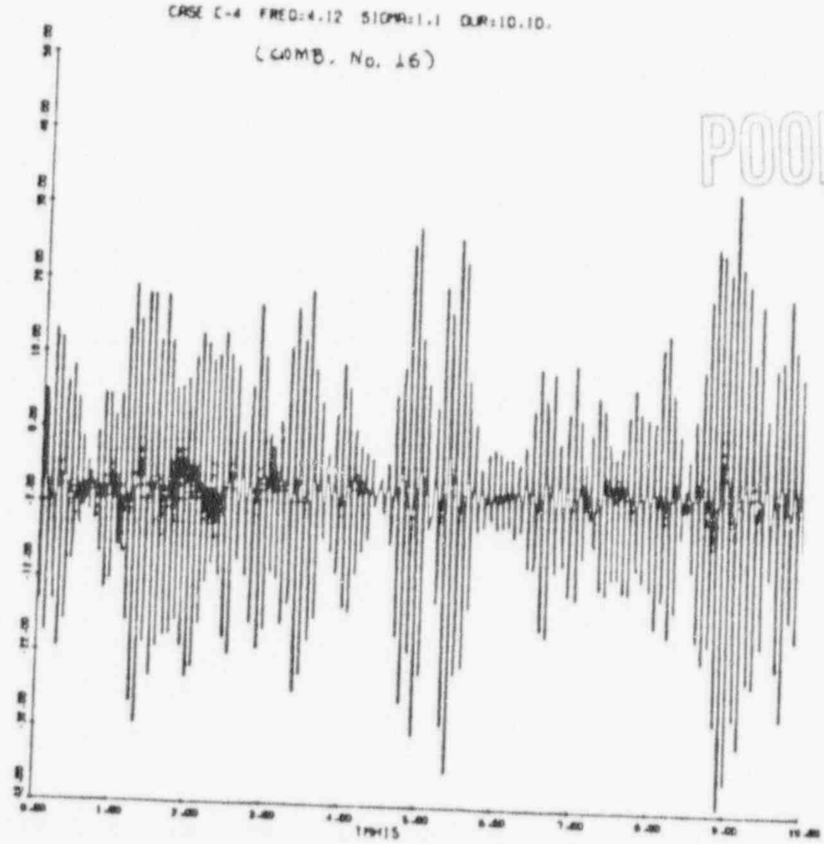


CASE C-4 FREQ:4.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 16)

4.5c

POOR ORIGINAL

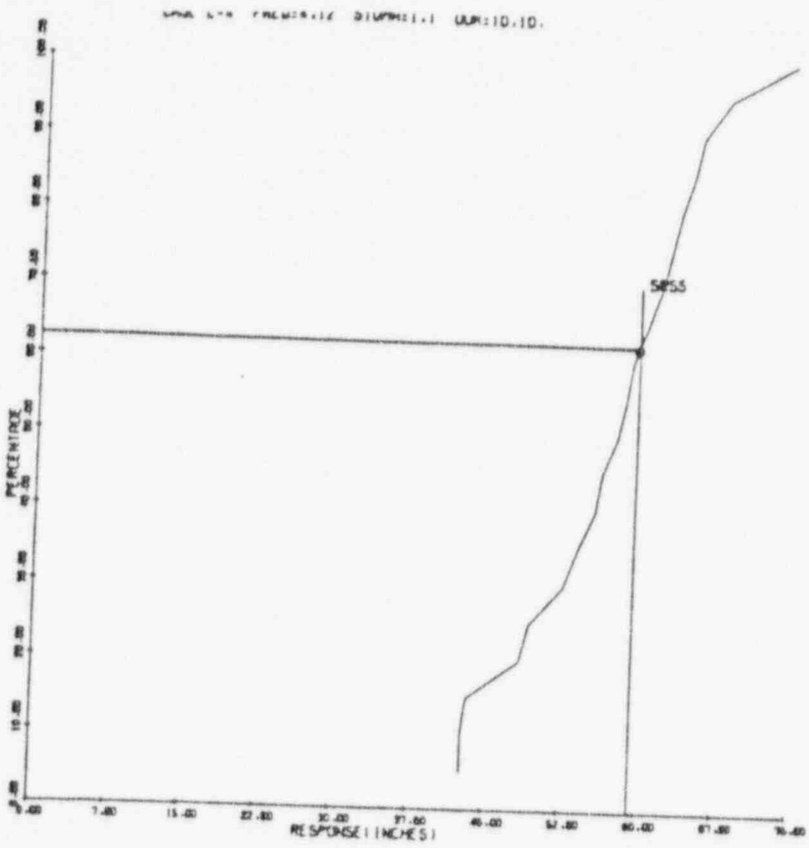


CASE C-4 FREQ:4.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 16)

4.5d

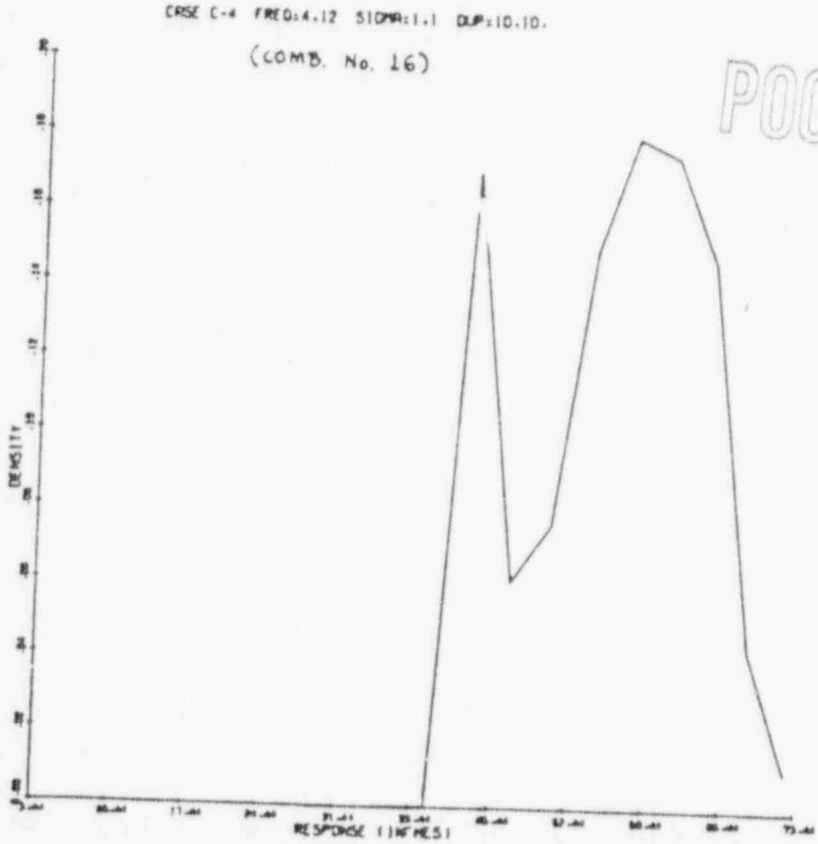
90011063



CASE C-4 FREQ:4.12 SIGMA:1.1 DUR:10.10.

(COMB. No. 16)

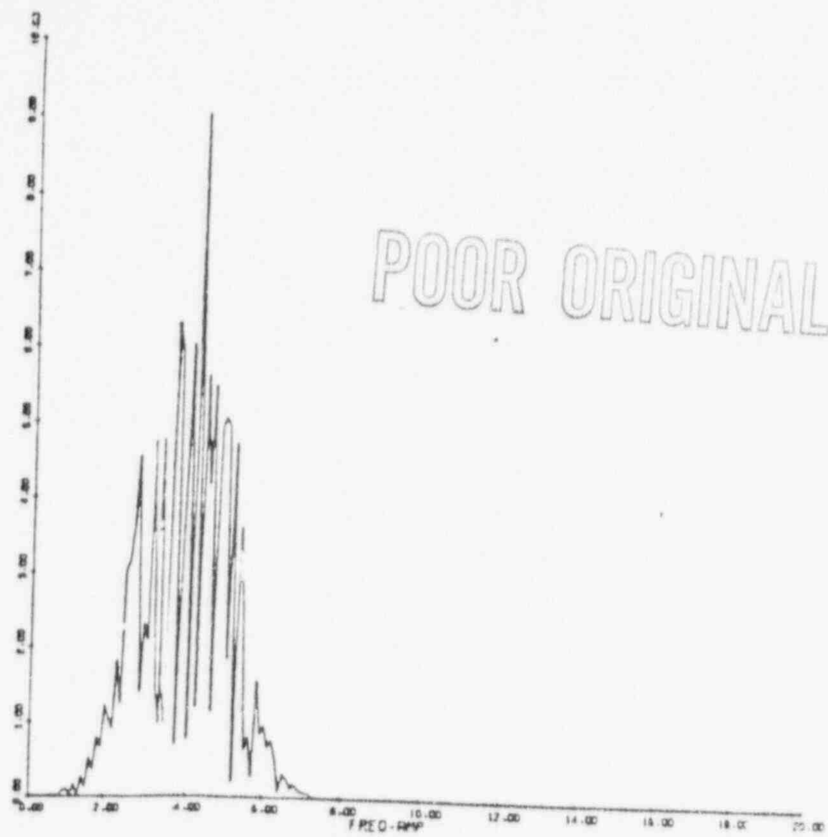
4.5e



CASE C-4 FREQ:' 12 SIGMA:1.1 DUR:10.10.

(COMB. No. 16)

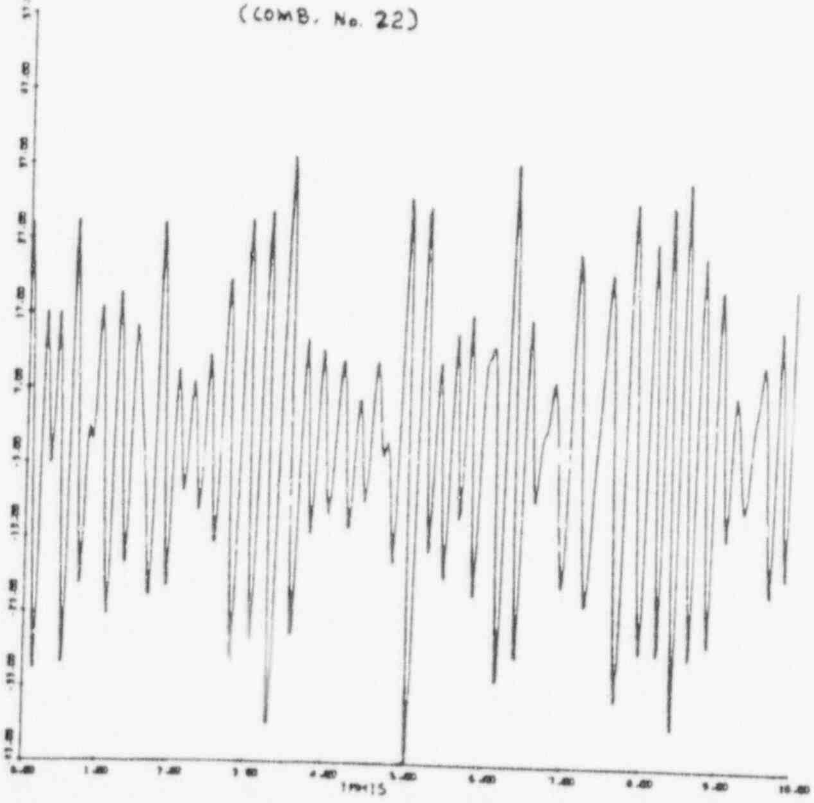
4.5f



CASE D-4 FREQ:4.12 SIGMA:1.1 DUR:10.5.

(COMB. No. 22)

4.6a



CASE D-4 FREQ:4.12 SIGMA:1.1 DUR:10.5.

(COMB. No. 22)

4.6b

90011065

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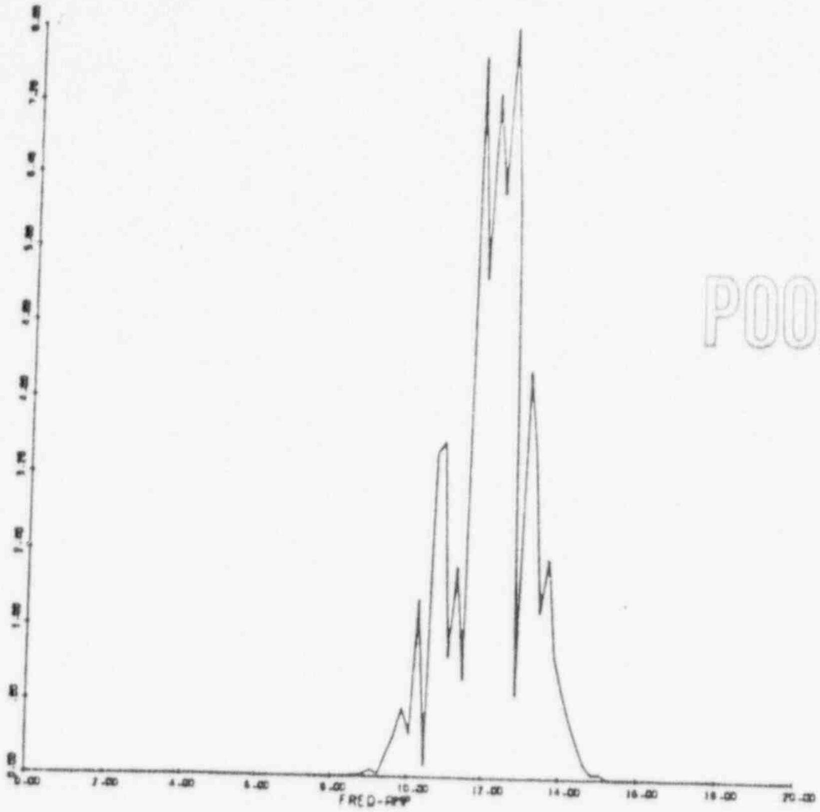
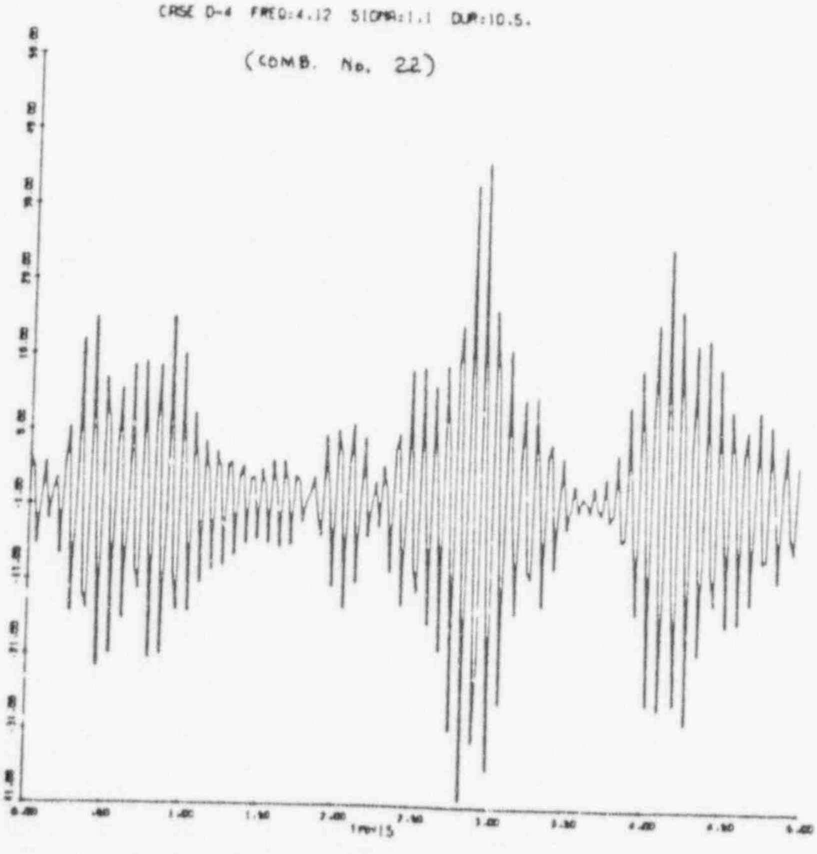
POOR ORIGINAL



CASE D-4 FREQ:4.12 SIGMA:1.1 DUR:10.5.

(COMB. No. 22)

4.6c

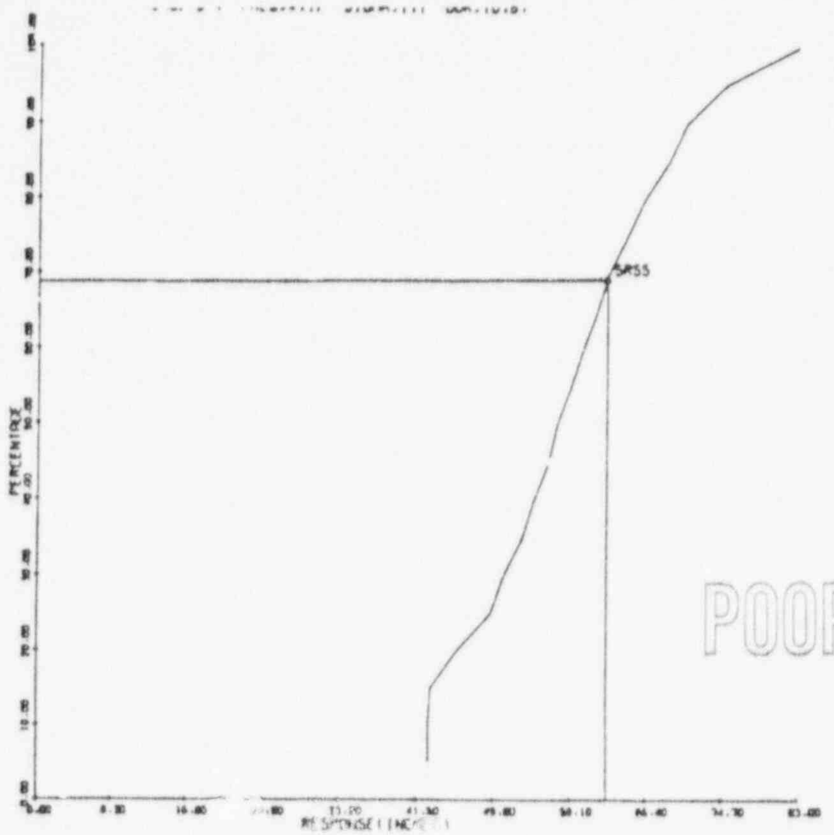


CASE D-4 FREQ:4.12 SIGMA:1.1 DUR:10.5.

(COMB. No. 22)

4.6d

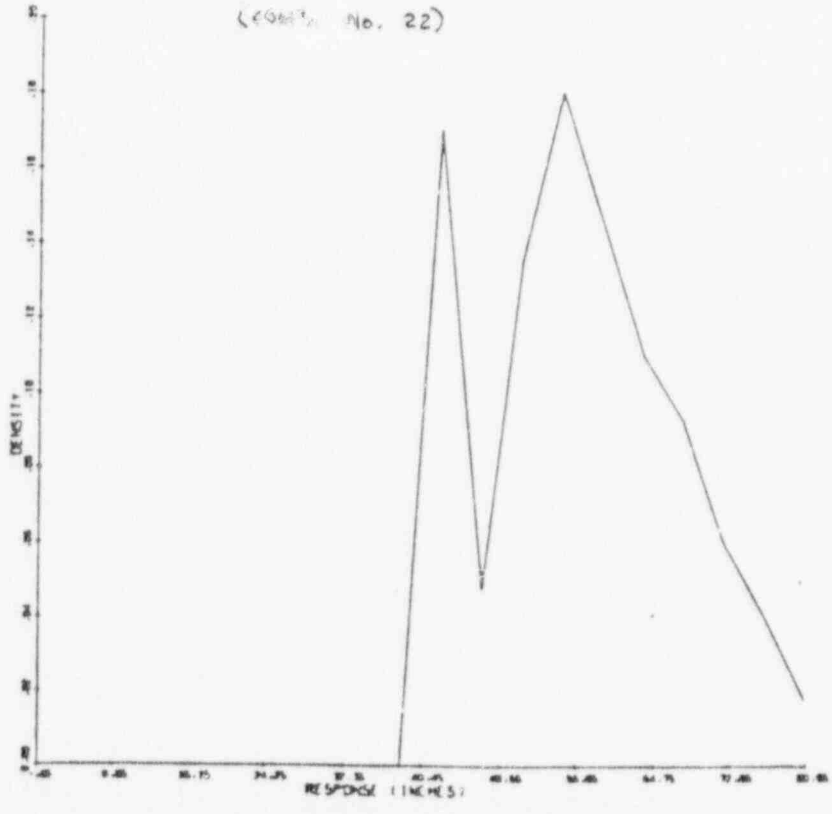
90011066



CASE D-4 FREQ:4.12 SIGMA:1.1 DUR:10.5.

(COMB. No. 22)

4.6e



CASE D-4 FREQ:4.12 SIGMA:1.1 DUR:10.5.

(COMB. No. 22)

4.6f

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V. COMBINATION OF ARTIFICIAL RESPONSES IN THE TIME DOMAIN

5.1 Purpose

Artificial responses can also be generated in the time domain. In this way additional parameters beside those provided by frequency content can be incorporated for investigation. These parameters include (1) the occurrence time of the peak responses of the component signal, (2) the distribution of response peaks of each individual signal, (3) envelope shape of the signals, (4) sparsity of peaks, (5) filtering frequency. These parameters were systematically changed in order to study the effects on the combined responses in the time domain.

5.2 Method of Generating Responses in Time Domain

Artificial responses in time domain can be generated following the expression:

$$R(t) = \int_{0}^{t} h(t-\tau)\psi(\tau)V(\tau)dt \tag{5.1}$$

where $h(t)$ is a frequency controlling filter. In the present case the filter is represented mathematically as follows:

$$h(t) = \frac{1}{\omega_d} e^{-\zeta\omega_{a\tau}} \sin \omega_{d\tau} \tag{5.2}$$

where ω_a is the controlling filtered frequency, ζ is the damping ratio and $\omega_d = \omega_a \sqrt{1 - \zeta^2}$. $\psi(\tau)$ in Equation (5.1) is a shape function used to modify the envelope of the response peaks so that there is an initial rising phase and a final decaying phase, $V(\tau)$ is a normally distributed random number used to control the peak distribution. Similar to the procedure described in Section 4.2, sets of artificial responses were generated directly in the time domain and were then combined, based on the random time lag of the component signals. The CDF curve and the NEP of the SRSS were then graphically plotted by the computer code.

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TABLE 5.1

Summary of Results for Combining Two Responses Produced in Time Domain

Comb. No.	Comp. No.	Peak Distrib.	Rising τ Duration	Decay τ Duration	Filter ω (rps)	No. of Peaks> 75%	60%	$\sigma / \overline{R}_{max}$	P(R<SRSS)
23	1 2	Gaussian Distribution with filter	.25	.25	5.0	6	20	.276	.87
24	1 2		.15	.15	5.0	10	24	.301	.72
25	1 2		.05	.15	5.0	15	34	.328	.63
26	1 2		.15	.15	20.0	3	14	.281	.86
27	1 2		.20 .10	.10 .10	10.0 7.5	15 8	37 13	.335 .357 .377	.66
28	1 2	Gaussian No filter	.25	0.0	no	28	51	.376	.60
29	1 2	Unif. Dist. No filter	.25	0	no	43	86	.405	.29

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5.3 Summary of Results

A summary of the results of combined artificial responses produced in the time domain is given in Table 5.1. It appears that the main influence affecting the probability distribution of the combined result is the distribution of the peaks of the component responses. Thus two columns are provided in the table. One column relates the number of peaks exceeding the 60% and 75% of the maximum peak value while the other is the ratio of the standard deviation σ to the maximum peak value R_{max} of the component signals. The significance of $\frac{\sigma}{R_{max}}$ has been stated in Section IV.

5.4 Conclusions

From the results shown in Table 5.1, the following conclusions can be drawn in regard to the combination of responses generated in the time domain.

1. The larger the number of peaks passing the 60% and 75% of the maximum peak values the lower will be the NEP of the SRSS. However, the peak count should be based on a rational scheme which includes the width (in time scale) of the peaks. In other words, peak count should reflect the percentage of the time of the response above a certain level of the signal.

2. Based on the above reasoning a more realistic approach appears to be that the NEP of SRSS is dependent on σ/R_{max} value of the individual responses where σ is the standard deviation of the digitized response distributions or

$$\sigma_i = \left(\frac{\Sigma\ R_i^2}{N}\right)^{\frac{1}{2}} \quad \text{for the response} \qquad (5.2)$$

and R_{max} is the maximum absolute value of the peak response. As shown in the table, when the σ/R_{max} value becomes larger the NEP of SRSS becomes smaller.

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3. The envelope shape of the response appears to play an important role. As the ratio of rising or decaying time to the duration of the signal increases, the NEP of the SRSS decreases.

4. When combining two signals if the duration of signal is much shorter than the first signal, then the combined response has a relative high NEP of the SRSS.

5.5 Sample Combinations of Dynamic Responses in Time Domain

Three sample cases of combinations in the time domain are depicted in figures 6.1-6.3. for each case the first figure, a, shows the time history while the second figure, b, shows the location of the SRSS on the CDF plot.

Case 1 = Two identical responses (comb. No. 27)
Gaussian peak distributions
with filter

Case 2 = Two identical responses (comb. No. 28)
Gaussian peak distributions
no filter

Case 3 = Two identical responses (comb. No. 29)
uniform peak distributions
no filter

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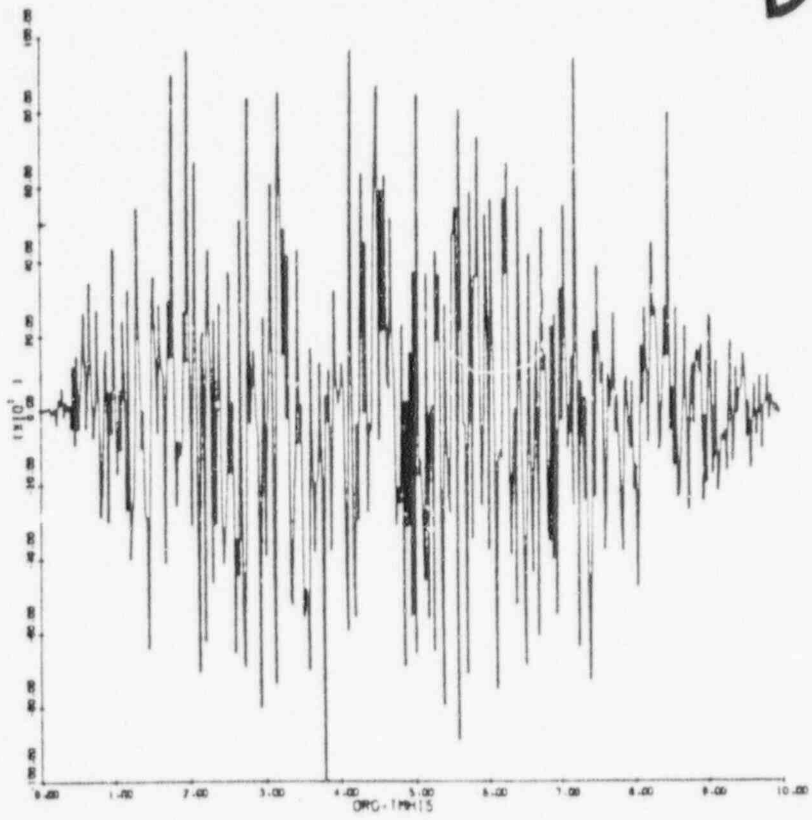
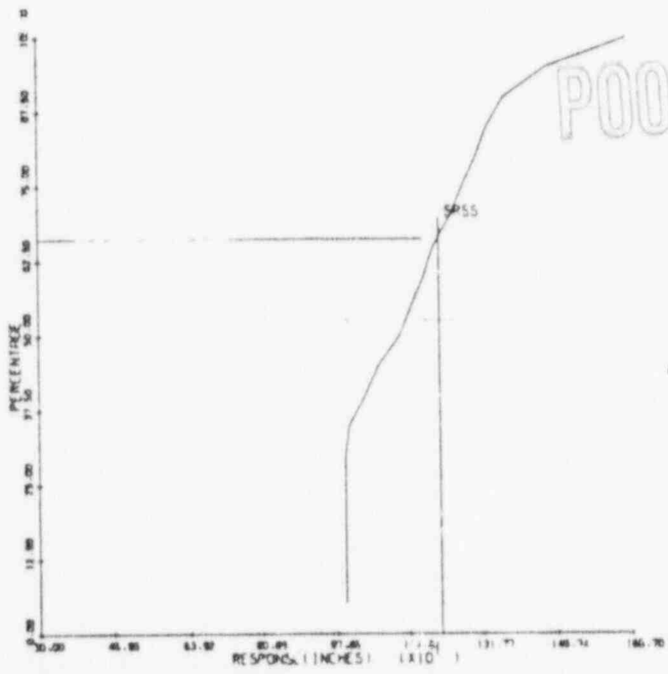


6.1a



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6.1b

Case 1
(Comb. 27)

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POOR ORIGINAL

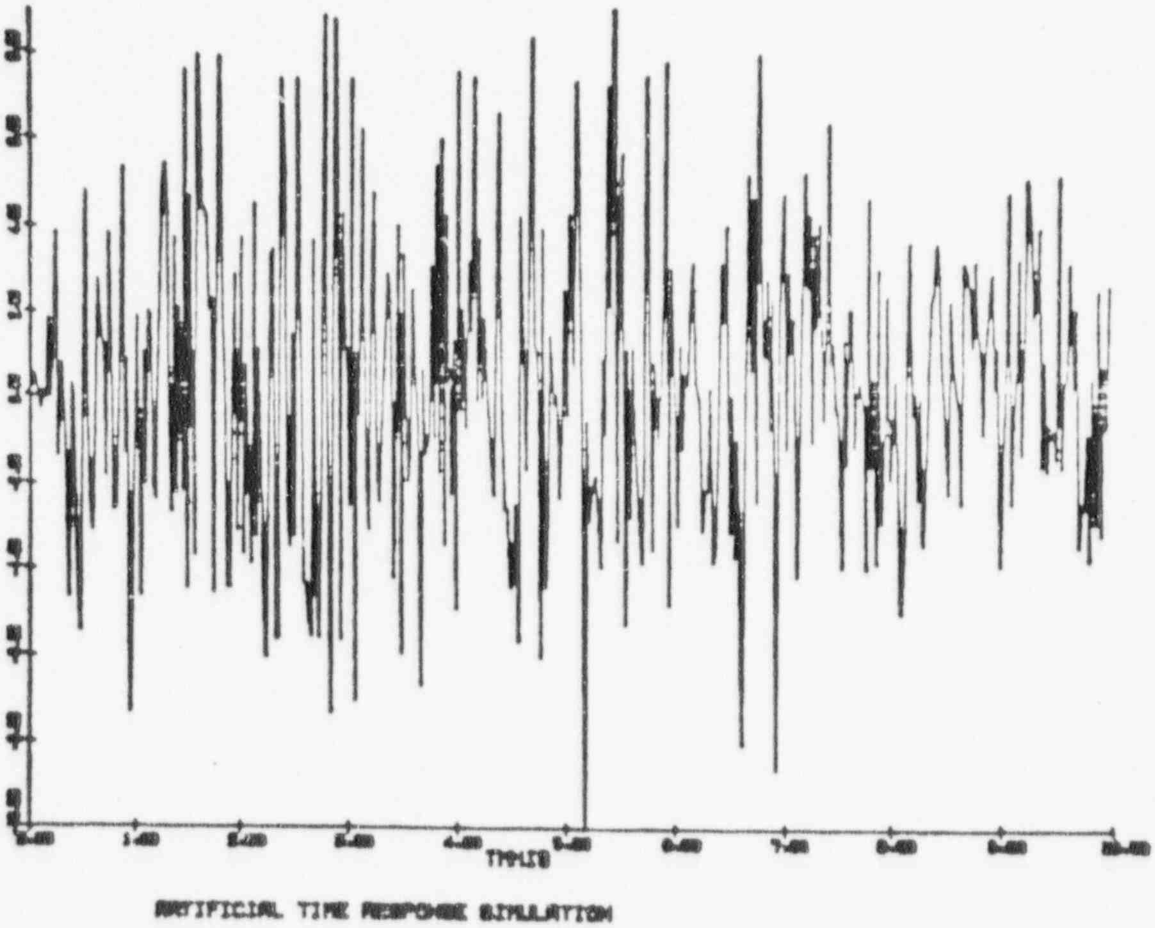

Fig. 6.2a

Case 2

Comb. 28 GAUSSIAN DIST OF PEAK
NO FILTER

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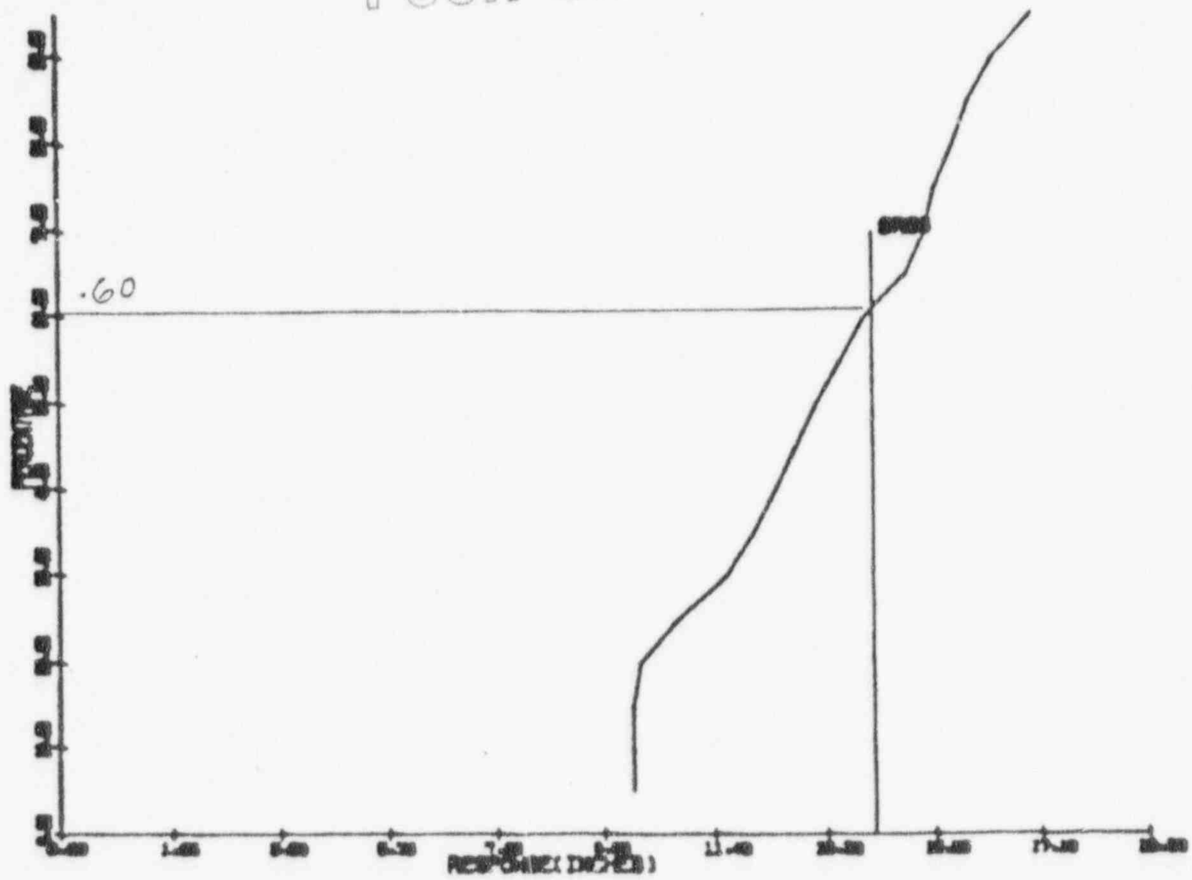
POOR ORIGINAL



ARTIFICIAL TIME RESPONSE SIMULATION

Fig. 6.2b

Case 2

Comb 28 GAUSSIAN DIST OF PEAK
NO FILTER

90011074

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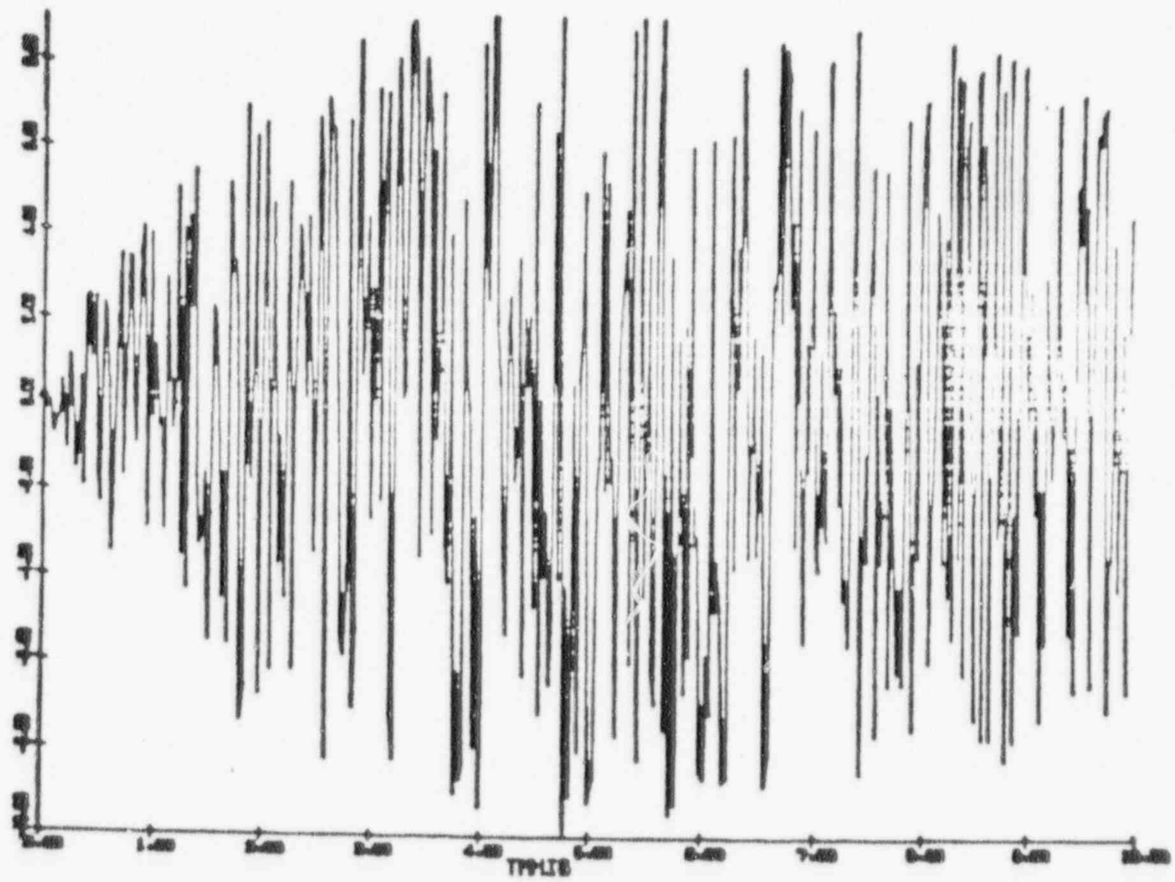
POOR ORIGINAL



ARTIFICIAL TIME RESPONSE SIMULATION

Case 3

Comb. 29. UNIF. DIST OF PEAK
NO FILTER

Fig. 6.3a

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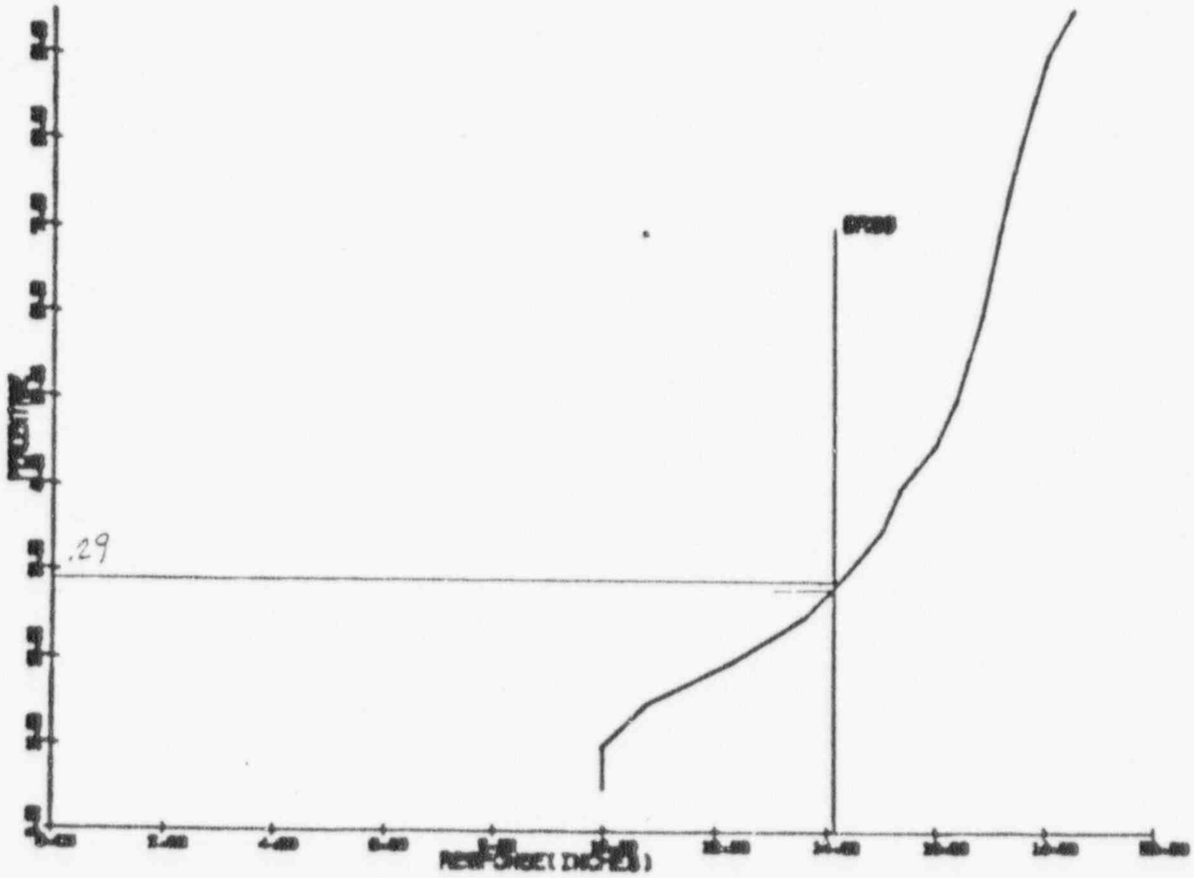
POOR ORIGINAL



ARTIFICIAL TIME RESPONSE SIMULATION

Case 3

Comb. 29. UNIF. DIST. OF PEAK
NO FILTER

Fig. 6.3b

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VI. EVALUATION OF MARK II RESPONSE COMBINATION CRITERIA

6.1 Background

Structures and components of nuclear power facilities are designed for a large number of load combinations. These load combinations include both multiple dynamic loads and static loads. In most cases, peak responses from each of the dynamic loads are calculated elastically. These results are then combined to obtain a resultant peak combined dynamic response. Once the resultant peak combined dynamic response has been determined from a combination of the multiple peak dynamic responses, the resultant is added absolutely to the elastically calculated static response. This elastically calculated combined maximum response is then compared to code allowable stress levels with the acceptance criterion being that the combined response must be lower than the code allowable level.

The question of how to obtain the resultant peak combined dynamic response of structures and components has been a concern of the Nuclear Regulatory Commission and the power plant designers. General Electric Topical Report NEDO-24010-2, entitled "Basis for Criteria for Combination of Earthquake and Other Transient Responses by the Square Root Sum of the Square Method", Supplement 2, was issued in December, 1978, addressing this problem. The report proposes two criteria as a basis for dynamic load combinations. This section reviews Criterion 1. Section 7 discusses Criterion 2.

6.2 Objective

The objective of this program is to obtain an evaluation of the areas of validity, adequacy, limitations and applicability of the two criteria in NEDO-24010-2.

6.3 Evaluation Procedure

To carry out the objective, the references cited in NEDO-24010-2 were reviewed. Most of the references deal with research findings on earthquake

responses. They mainly show that extensive work has been carried out to assure that both excitation and responses are random in nature. Statistical evaluations are also well documented to establish the non-exceedance probability of the excitation at the 84 percent level. However, very little information is available to ascertain that other transient excitations (SRV, LOCA, etc.) and responses are earthquake-like and that their non-exceedance probability is at the 84 percent level. The literature did not turn up other criteria that were similar to either of the two criteria under study and that could be used as guidance. Accordingly, five specific tasks were identified which would permit an evaluation of Criterion 1. These include:

A) Clarify the extent to which combinations of responses should only be based on the characteristics of the response time functions as opposed to the loading time functions. This clarification will be limited to computer runs with simple systems containing a few degrees of freedom.

B) Using Monte Carlo simulation verify with real and simulated response functions whether the basis of limited number of high peaks (i.e., 5 or less exceeding 75 percent of maximum and 10 or less exceeding 60 percent of the maximum) is always acceptable. If not acceptable determine alternate limitations.

C) Using Monte Carlo simulation investigate the extent to which departures from zero mean affect the acceptability of Criterion 1. Consider in this investigation the variety of ways zero mean can be attained over different time durations.

D) Using Monte Carlo simulation investigate the effect of the variation of signal duration time on the applicability of Criterion 1.

E) Using Monte Carlo simulation investigate, using various values of correlation coefficient, the acceptability of an equal or less than 0.4 value of correlation coefficient for the SRSS methodology.

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Each of these specific tasks were investigated. The procedures used and the results obtained will now be discussed.

6.4 Clarification of Characteristics of Load and Response Time Histories

Criterion 1 indicates that the combination of responses could be done either by examining the response signals or by examining the loadings themselves. When earthquake responses are obtained by using response spectra, no time history of the response function will be available. Criterion 1 of NEDO-24010-2 recommends that in lieu of the response functions, the input functions can be used to judge the adequacy of combinations based on the SRSS rule. This recommendation appears to be based on the reasoning that the response functions are generally more favorable towards the SRSS rule. This means that the response time functions are less likely to have their peaks combine, in which case the non-exceedance probability should increase and the use of SRSS should be conservative.

To clarify the extent to which combinations of responses should be based only on the characteristics of the response time function as opposed to the loading time functions, simple response computer analyses were carried out on a Hovgaard bend piping system with over fifty degrees-of-freedom, as shown in Figure 6.1. The system is a three-dimensional pipe bend arrangement in which the legs are at right angles to each other and are connected by ninety degree bends. The basic dynamic characteristics of the pipe bend were varied both in terms of damping and in terms of stiffness. Values were selected so that the fundamental natural frequency of the piping system was located beyond the high end of the exciting spectrum, within the band of highest excitation and at the low end of the earthquake frequency range. Damping was varied over a range of from zero to seven percent.

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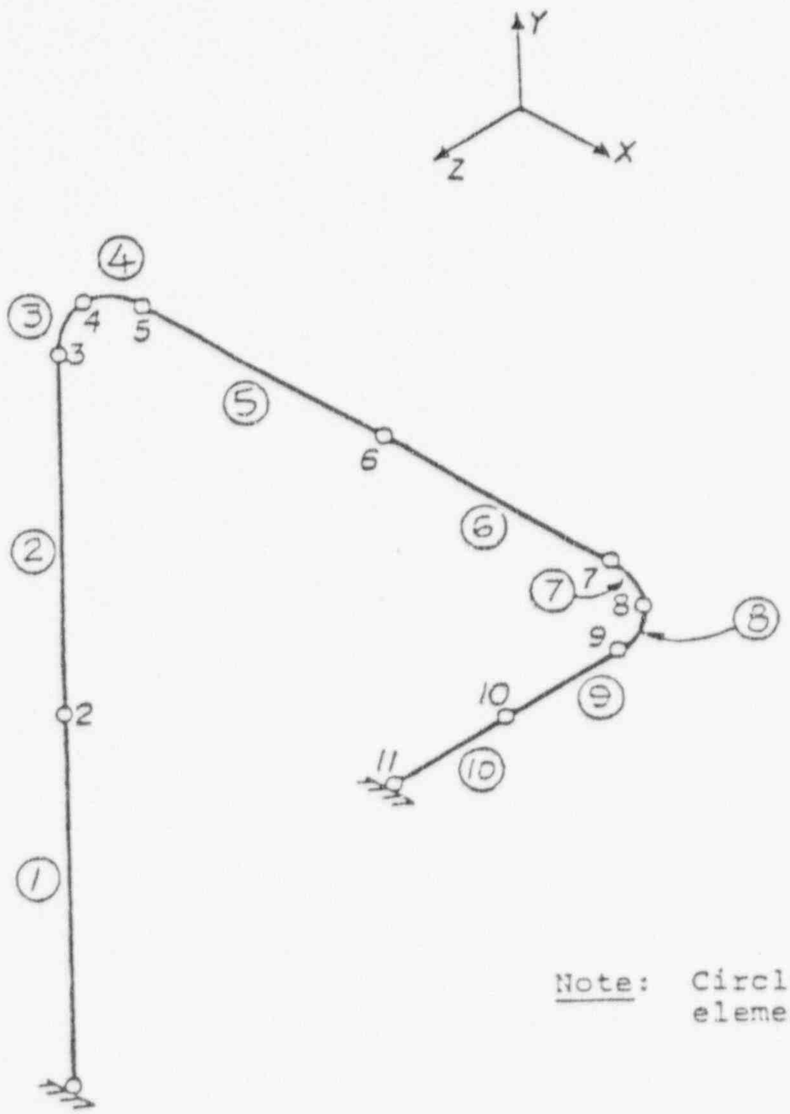

Note: Circles represent elements.

Fig. 6.1

LUMPED MASS SYSTEM FOR HOVGAARD BEND

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Excitations were applied and responses were obtained for each of the different conditions. The piping system was subjected to ground motion of the Imperial Valley Earthquake, El Centro Site, May, 1940 in the SOOE direction, as shown in Figure 6.2. The excitation was applied along a skew axis.

Responses in terms of acceleration, forces, and moments were printed out at each of the nodal points. These were compared to the loading time function. The basis for the comparison was in terms of the number of peaks exceeding certain percentages of the maximum. Two different approaches were used to count the peaks.

In the computer printout procedure, digitized information was recorded at discrete time intervals of 0.025 seconds. This was done both for the input loading time functon as well as for the response time function. The number of peaks in each interval was counted. A record was made of the number of peaks exceeding various percentages of the maximum from 50 percent to 95 percent in 5 percent intervals. For each time interval in which the amplitude exceeded a certain percentage of maximum, a peak was counted. In cases where the amplitude remains above the level for several time intervals, it is counted several times. This was done in all cases, both for the input excitations as well as for the responses. The number of peaks exceeding the various percentages of maximum were compared.

In the second procedure, graphical plots were obtained for the input loading and output responses. Lines were drawn to separate and to identify when the amplitude exceeds 75 percent and 60 percent of the maximum. Comparisons were made of the number of peaks in each category for the loading time histories and their corresponding responses.

Some of the results of the first procedure are shown in Table 6.1. The top row, above the double horizontal line, shows the number of peaks above the

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FIG. 2-2 TIME HISTORY ACCELERATION OF THE IMPERIAL VALLEY EARTHQUAKE El CENTRO SITE MAY 18, 1940 S00E DIRECTION

Fig. 6.2

TABLE 1

?.6 Hz 7% 1

INPUT

PEAK= 89.918 MEAN= .121

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500
NO. OF PEAKS PAS	63	55	39	22	12	11
FRACT OF T.U.T	.079	.069	.049	.028	.015	.014

TMMIS-X-2

PEAK= 25877.090 MEAN= 1.259

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500
NO. OF PEAKS PAS	57	45	33	22	19	17
FRACT OF T.U.T	.071	.056	.041	.028	.024	.021

TMMIS-Y-2

PEAK= 37.607 MEAN= -.002

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500
NO. OF PEAKS PAS	68	46	31	26	20	14
FRACT OF T.U.T	.085	.058	.039	.033	.025	.018

78

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TMMIS-Z-2

PEAK= 25602.349 MEAN= -3.256

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500
NO. OF PEAKS PAS	39	31	26	19	17	9
FRACT OF T.U.T	.049	.039	.033	.024	.021	.011

TMMIS-X-3

PEAK= 78050.607 MEAN= 4.060

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500
NO. OF PEAKS PAS	53	42	28	21	18	15
FRACT OF T.U.T	.066	.053	.035	.026	.023	.01[illegible]

TMMIS-Y-3

PEAK= 75.150 MEAN= -.004

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500
NO. OF PEAKS PAS	68	46	31	26	20	14
FRACT OF T.U.T	.085	.058	.039	.033	.025	.018

TMMIS-Z-3

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DR-1

TABLE 1 (CONTINUED)

FX-TM-4

PEAK= 13605.925 MEAN= -.309

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500	.7000
NO. OF PEAKS PAS	65	56	39	31	25	21	12
FRACT OF T.U.T	.081	.070	.049	.039	.031	.026	.015

FY-TM-4

PEAK= 16459.568 MEAN= .256

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500	.7000
NO. OF PEAKS PAS	54	37	29	24	18	13	8
FRACT OF T.U.T	.068	.046	.036	.030	.023	.016	.010

FZ-TM-4

PEAK= 13236.320 MEAN= .438

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500	.7000
NO. OF PEAKS PAS	42	36	26	21	18	15	9
FRACT OF T.U.T	.053	.045	.033	.026	.023	.019	.011

MX-TM-4

PEAK= 332557.698 MEAN= -10.082

79

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500	.7000
NO. OF PEAKS PAS	38	26	19	13	11	9	8
FRACT OF T.U.T	.048	.033	.024	.016	.014	.011	.010

MY-TM-4

PEAK= 227183.648 MEAN= 19.501

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500	.7000
NO. OF PEAKS PAS	48	34	28	17	14	11	6
FRACT OF T.U.T	.060	.043	.035	.021	.018	.014	.008

MZ-TM-4

PEAK= 135265.556 MEAN= -5.307

PERCENT OF PEAK	.4000	.4500	.5000	.5500	.6000	.6500	.7000
NO. OF PEAKS PAS	31	23	20	15	12	9	8
FRACT OF T.U.T	.039	.029	.025	.019	.015	.011	.010

ALUE OF J= 801

POOR ORIGINAL

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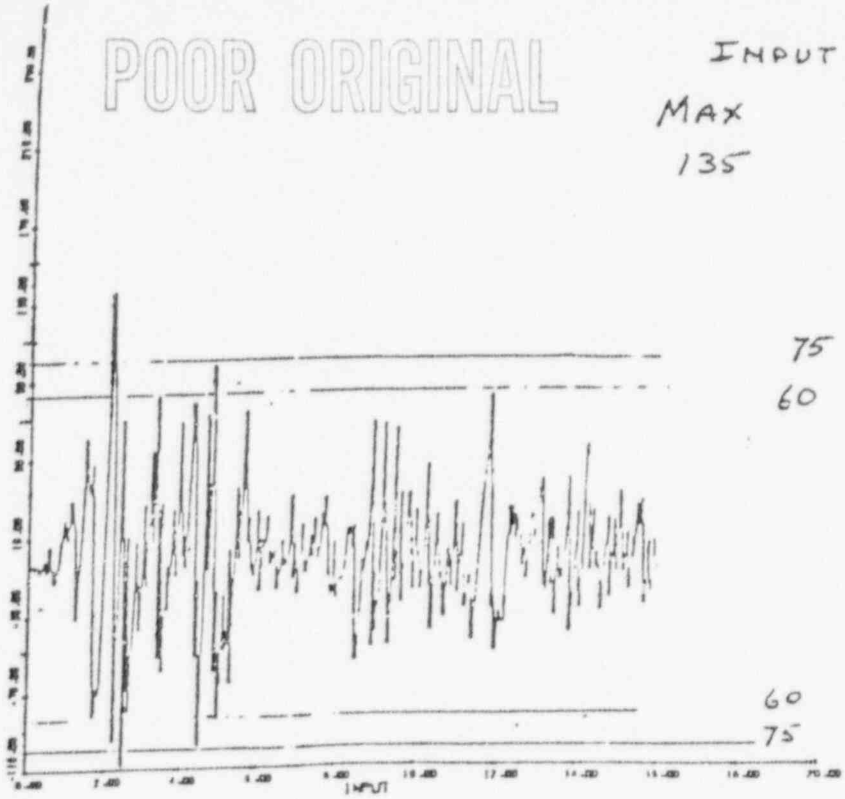
DRAFT

various percentages of the maximum for the input. For this particular loading, there were five peaks equal to or greater than 75 percent of maximum and twelve peaks equal to or greater than 60 percent of maximum. Below the double, horizontal line are the responses at the various nodal points. The numbers that are circled show the cases where the number of peaks that were recorded in the response exceed the number of peaks in the input loading.

A comparison between the loading and response is shown in Figure 6.3. The upper curve shows the input time history while the lower curve shows the force in the Y direction at node 2. Lines are drawn to identify the 60 and 75 percent levels. The number of peaks above these levels is listed in the right hand column. A peak was counted once as long as it remained above a particular level. When it dipped below the level, the peak was considered to have ended. The duration of time that it remained above the level was not considered. The peak was counted as more than one if it dipped below the level of interest and then rose above it again. Thus, for the positive peaks above 75% of maximum, two response peaks are counted for the response because the signal drops below the 75% line and then rises again. The number of positive peaks exceeding 75% and 60% of maximum is 1 and 3 for the input. This compares with 2 and 6 for the response. For negative peaks, the numbers are 1 and 4 for the input compared with 3 and 5 for the response. These numbers comfirm the comparison as obtained in the digitized first method. They show that the response can have more peaks than the input loadings. Note also that the width of the response peaks is greater than the width of the input peaks. With more peaks, and with wider peaks, the probability of peaks combining increases. This could lower the non-exceedance probability of the SRSS. Thus, it appears that the response combinations should be based upon the characteristics of the response time functions and not upon the loading time histories.

INPUT

MAX	75%	60%
135	101.25	81



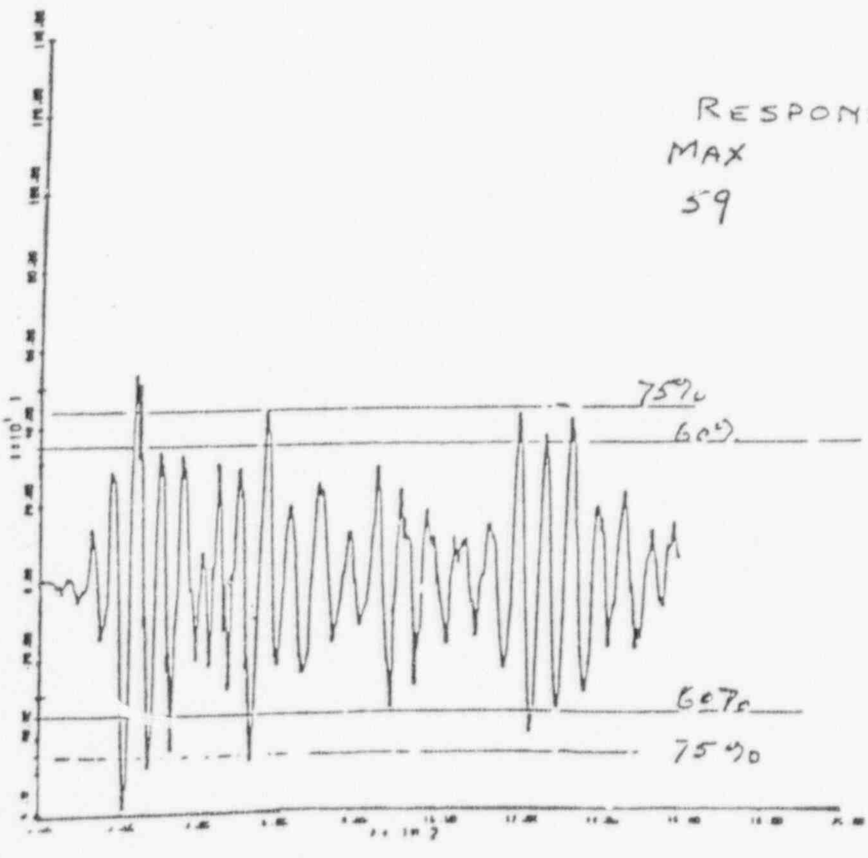
\# of PEAKS

1
3

4
1

RESPONSE

MAX	75%	60%
59	44.25	35.4



2
6

5
3

Fig. 6.3

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6.5 Effect of Number of Peaks

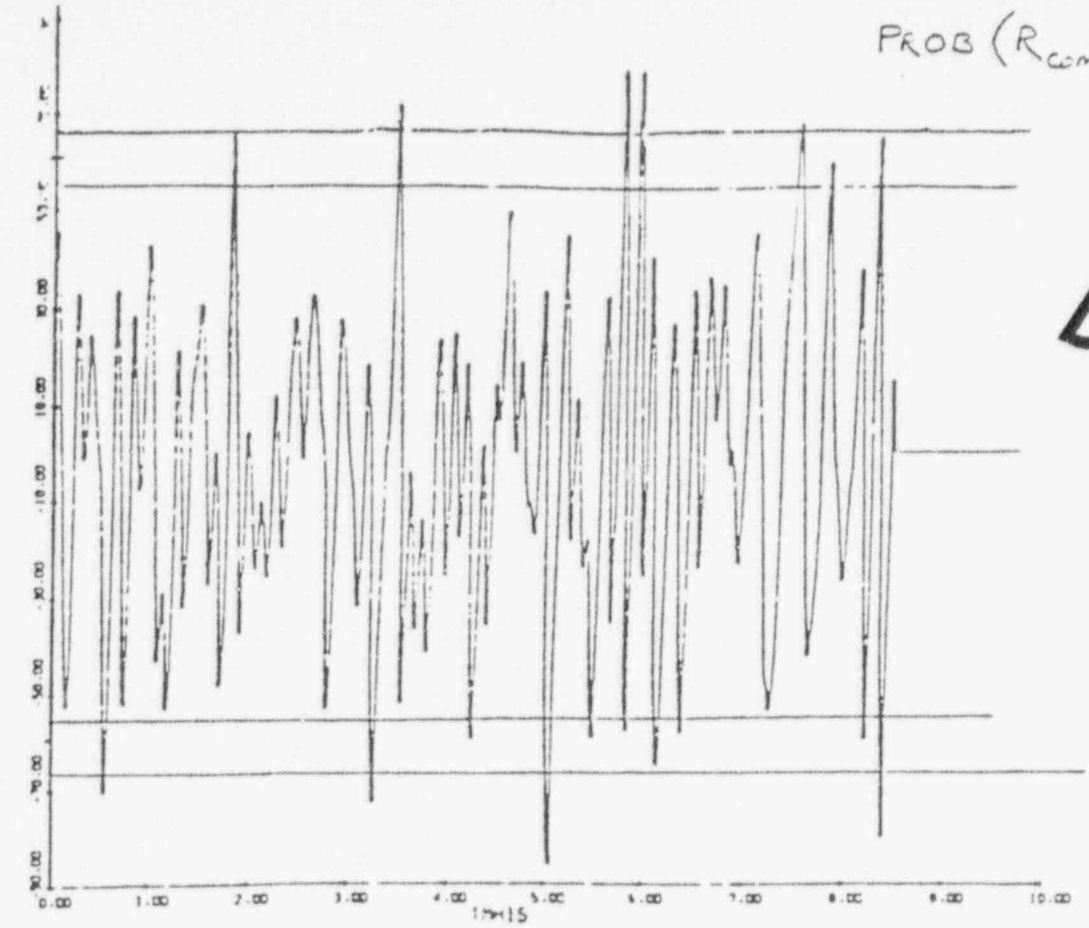
The use of basic number of peaks above certain percentages of maximum (i.e., five or less exceeding 75 percent of the maximum and ten or less exceeding 60 percent of the maximum) as a criteria appears to be capable of resulting in some non-conservative cases. Runs have been made with simulated earthquake-type signals. Some of the combinations have produced a CDF non-exceedance level curve on which the SRSS is less than 50 percent. One such case is shown in Figure 6.4 where the time response components have combined to produee a probability (R < SRSS) of 45 percent.

For the case of Figure 6.4, the first response signal has a basic frequency composition of between 1 and 7 Hz. This is a simulated response which was randomly generated to have a mean frequency of 4 Hz and a standard deviation of 3 Hz with a normal distribution. The second signal in the combination has a mean frequency of 12 Hz, again with $\sigma = \pm 3$ Hz. The first signal has a duration of 8.5 seconds while the second occurs for only 4.5 seconds. The numbers of peaks were counted from the plot of Figure 6.4 and are indicated at the 75% of maximum level and at the 60% level. It is seen that these signals are generally earthquake-like as far as numbers of peaks are concerned.

The curves were altered somewhat to examine the changes that would result in P(R < SRSS) if some of the peaks were eliminated, others shifted and some widened slightly. In addition, a short decay portion was added to each signal.

The first case, shown in Figure 6.5, uses the signals from Figure 6.4. Both signals are extended somewhat to add a short decay portion. In all cases, the numbers of peaks conform to the requirement of Criterion 1. Figure 6.5a and 6.5b are plots of both response signals which are combined with uniform distribution of time lag. Figure 6.5c shows the cumulative distribution function with

PROB (R_{COMB} < SR(55)) = 45



4 > 75%
7 > 60%

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4 > 75
10 > 60

CASE C-5 FREQ:4.17 SIGMA:3.3

RESPONSE COMP 1

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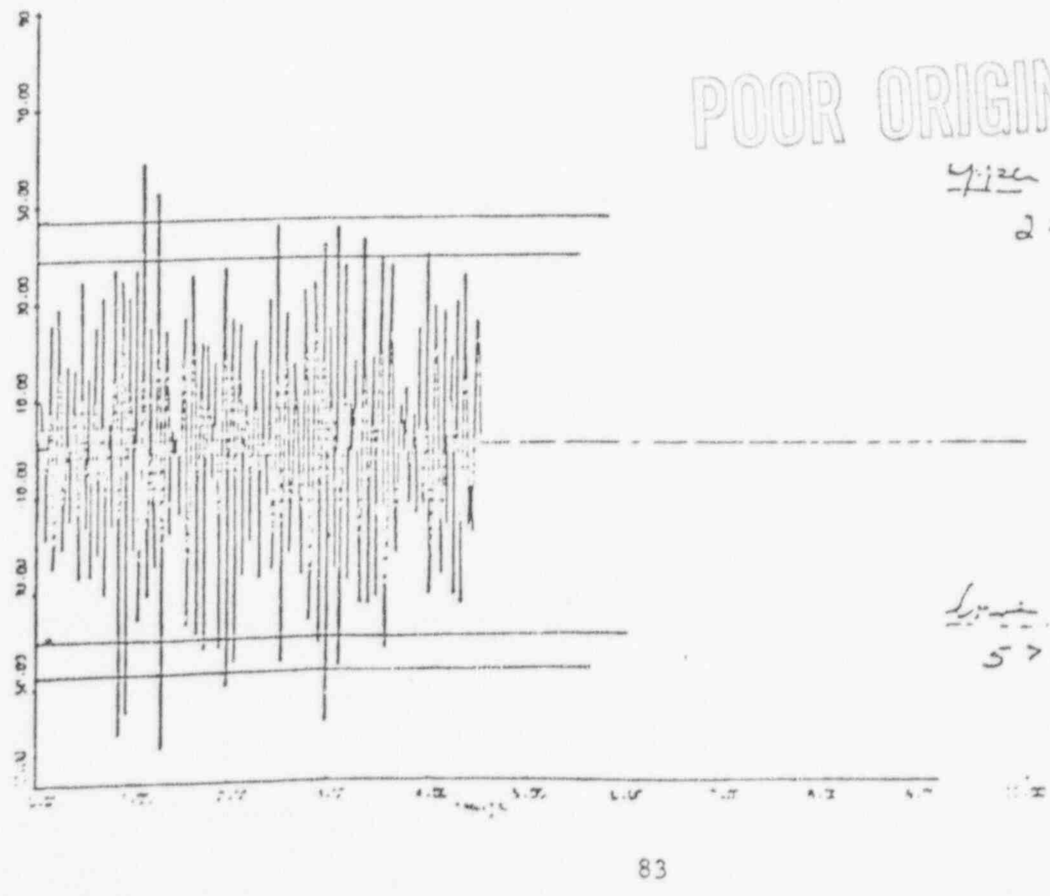

2 > 75   7 > 60

Fig. 6.4

5 > 75   12 > 60

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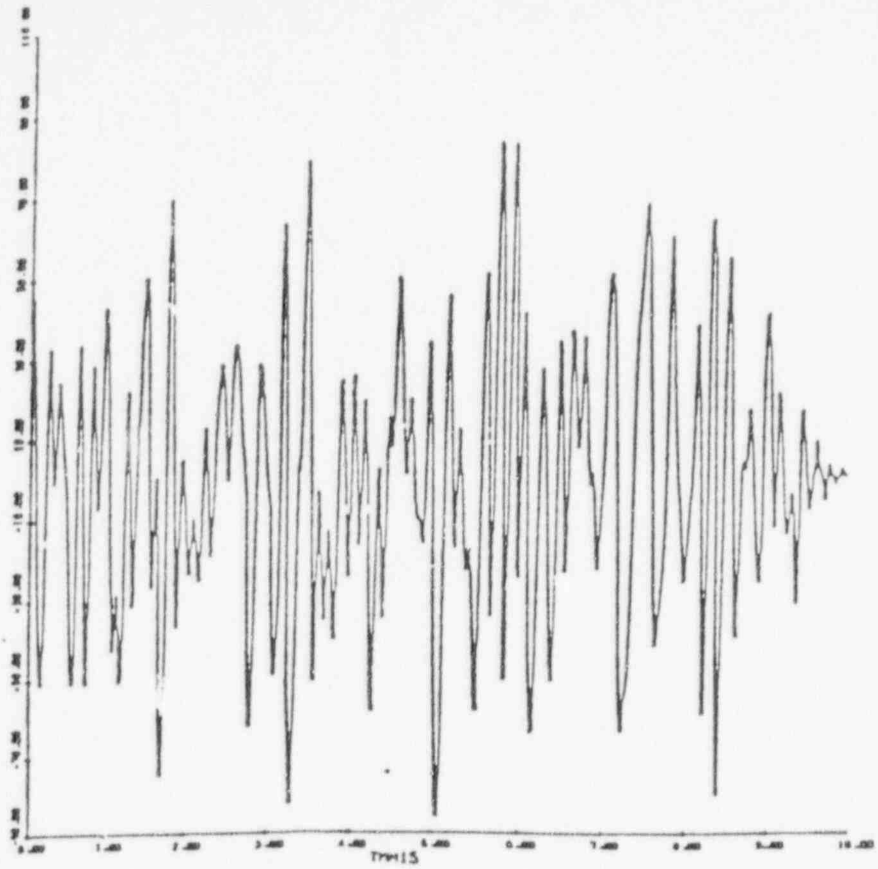
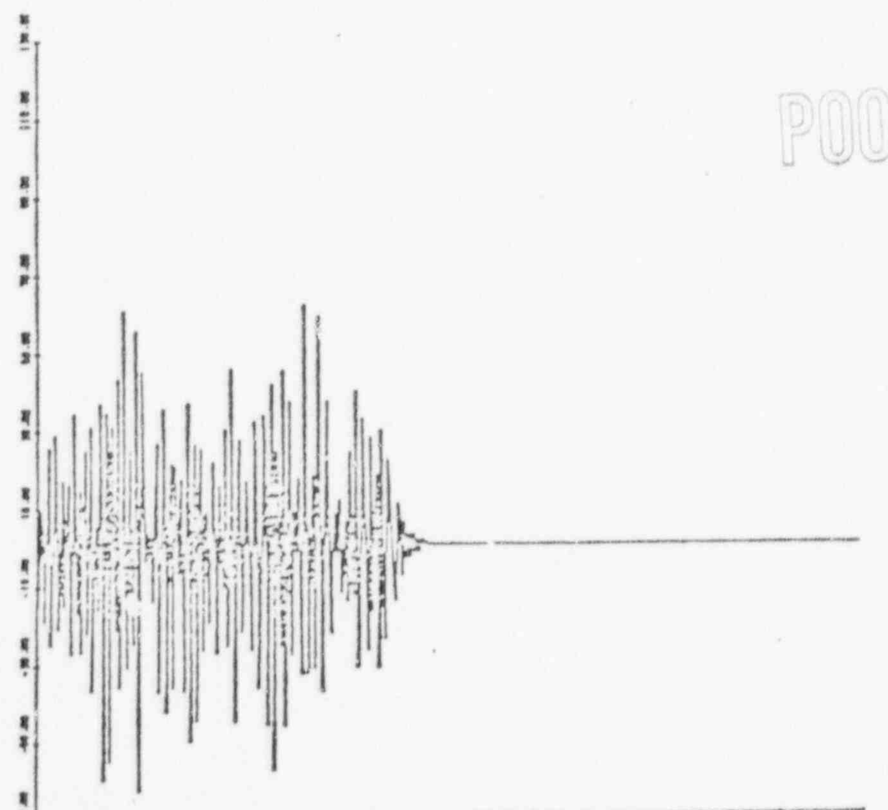
R_1



CASE C-5 FREQ=4.12 SIGMA=3.3 DUR=10.10.

6.5a

R_2

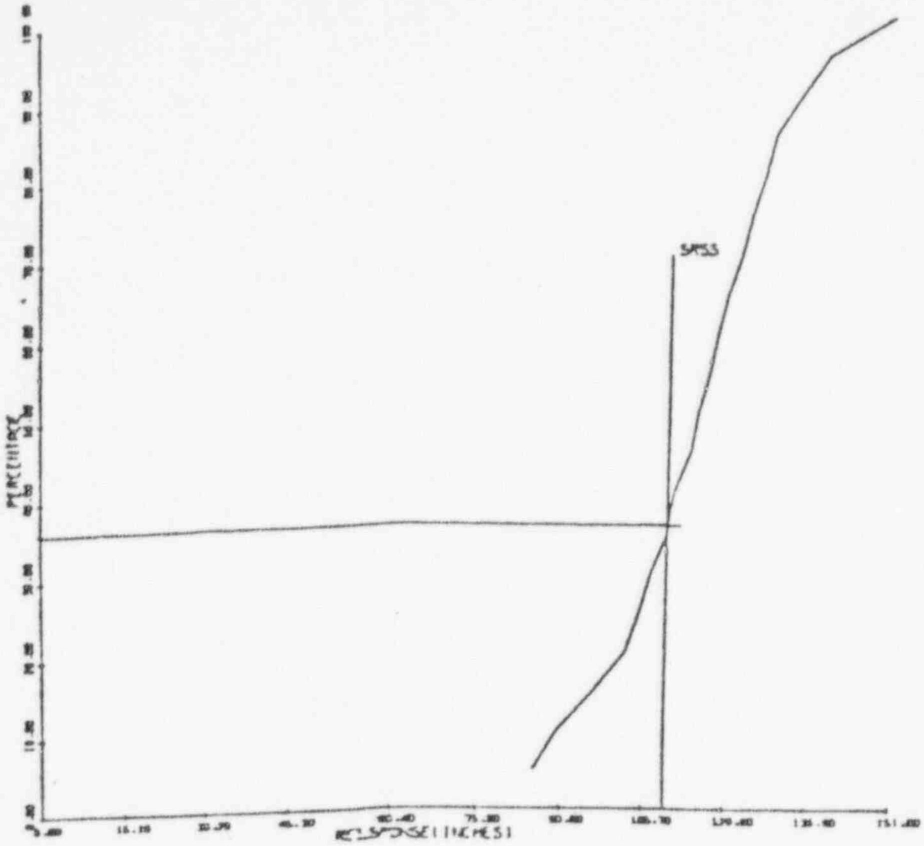


CASE C-5 FREQ=4.12 SIGMA=3.3 DUR=10.10.

6.5b

CASE C-5
(OCD)
10.0 / 4.75
P(R < SRSS) = 3:

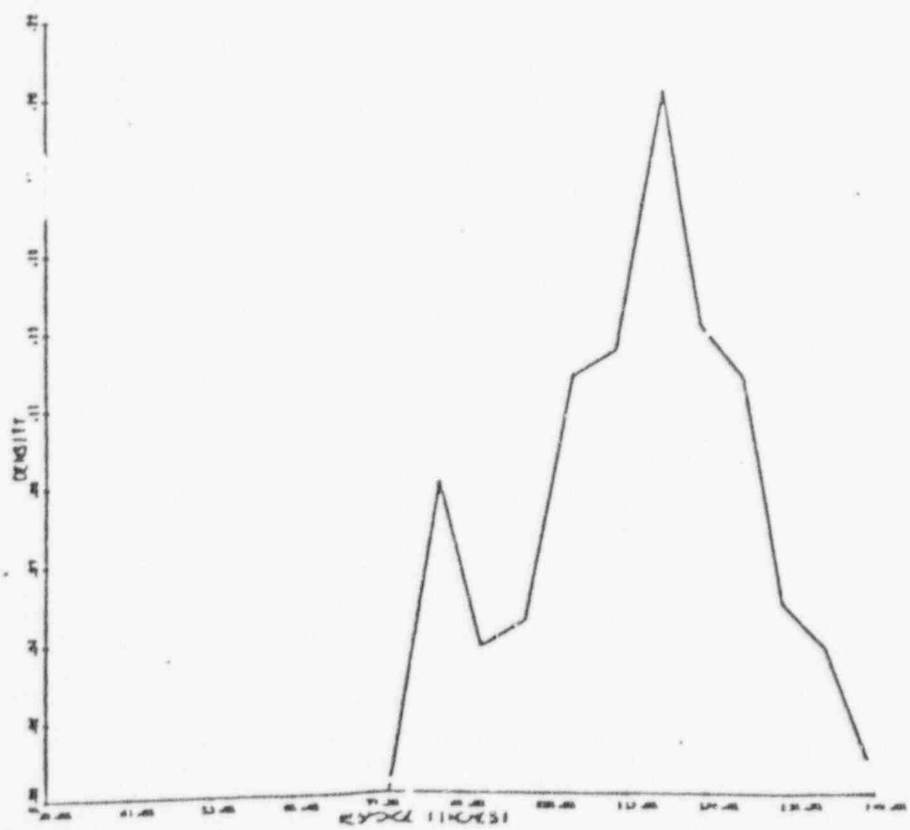
Fig. 6.5



CASE C-5 FRED:4.12 SIGMA:3.3 DUR:10.10.

35 %

6.5c



CASE C-5 FRED:4.12 SIGMA:3.3 DUR:10.10.

6.5d

CASE C-5
(OCD)
10.0/4.75

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the SRSS superimposed and Figure 6.5d shows the probability density function. It is seen that the NEP of SRSS is 35% in this case.

A final case will be reported in this section. The response signals shown in Figure 6.6 were combined. They were generated by the same procedure as was described for the previous case shown in Figure 6.5. The first signal has a mean frequency of 12 Hz and a standard deviation of 5 Hz with a normal distribution. The second signal has a mean frequency of 6 Hz and a standard deviation of 5 Hz. Figure 6.6c shows that the NEP of SRSS for this case was 29%.

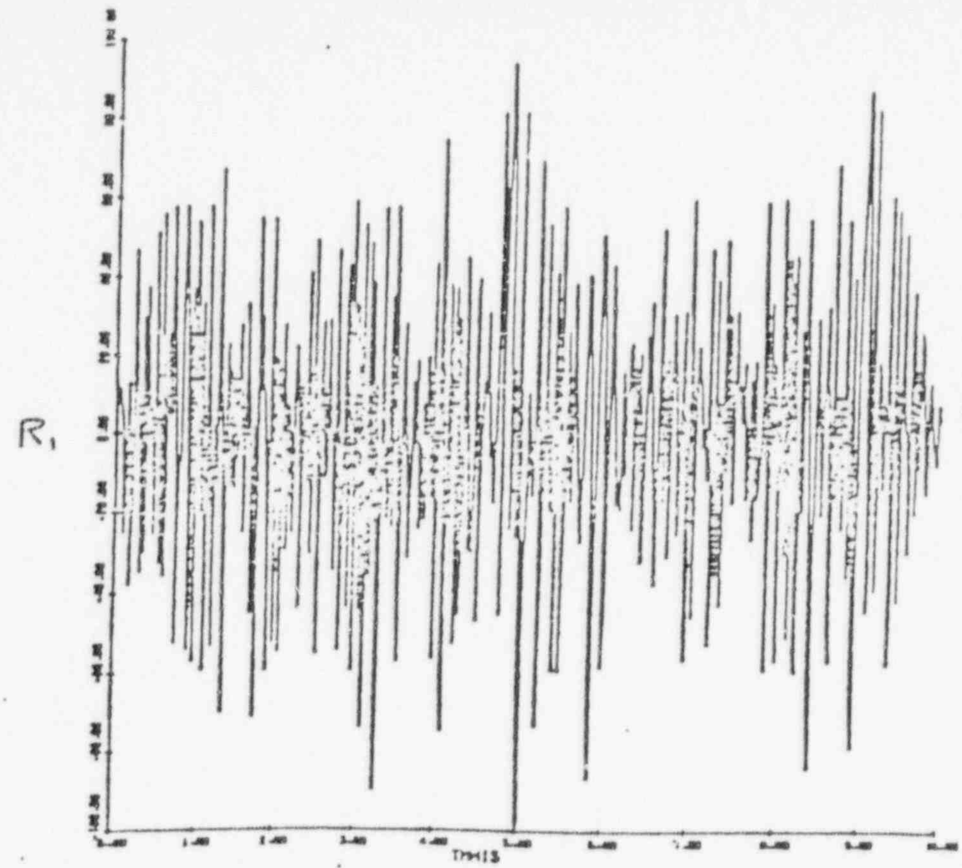
These are cases where the signals that have been combined have few peaks, as defined by the criterion. They have been shown to have the NEP of SRSS at less than the 50 percent level. Furthermore, in applying the criterion, other questions have occurred. Counting the number of peaks does not account for the width of the peak. Actually, as shown by the sinusoidal studies, the number of peaks as well as the total time that a strong signal is present are both factors in establishing the location of the SRSS or the CDF curve. In some cases, there is a question regarding the number of peaks since the signal drops slightly before it rises again. This type of characteristic increases its width but still might permit describing it as one peak.

In summary, in reviewing the validity of using SRSS for combinations, many questions and ambiguities arise . Specifically:

(a) The counting of peaks c.n be based on the plus or minus side only, or on both sides.

(b) The peak count changes depending on the scale size of the plot.

(c) When the time functions change rapidly, there are minor peaks in addition to major peaks. It is a question whether minor peaks should be included in the counting.



CASE C-3 FREQ=6.12 SIGMA=5.5 DUR=10.10.

5 > 75%
9 > 60%

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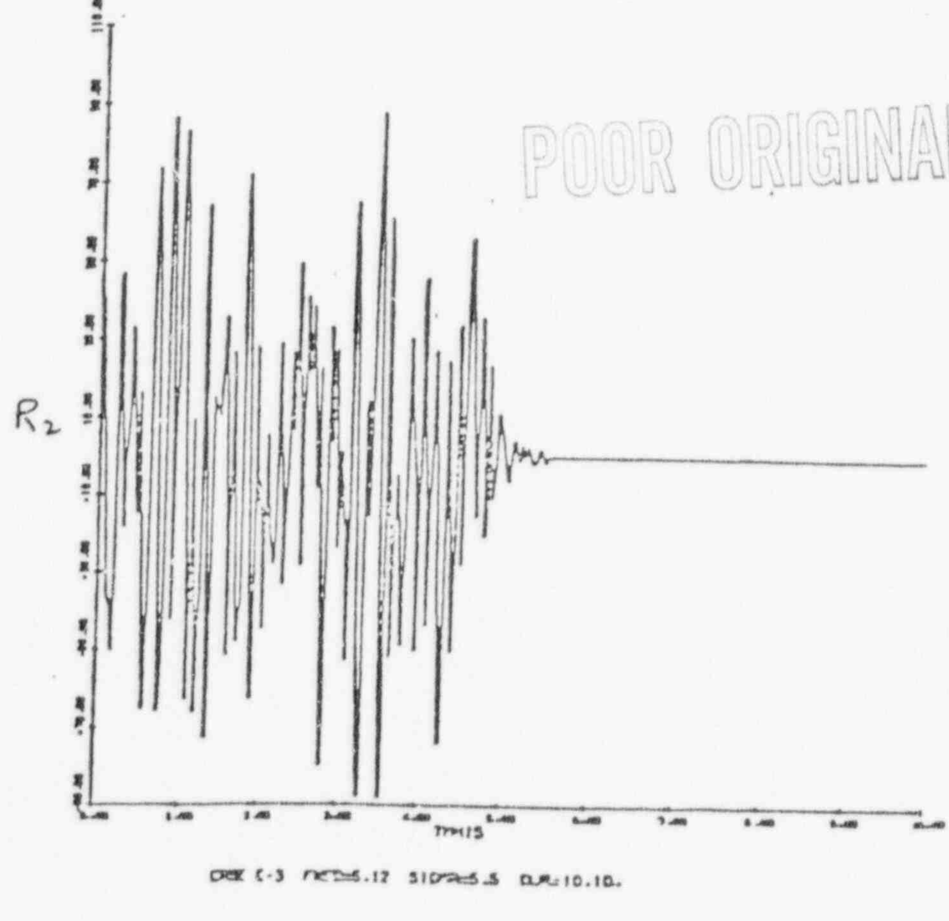
5 > 75%
10 > 60%

6.6a



CASE C-3 FREQ=5.12 SIGMA=5.5 DUR=10.10.

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5 > 75%
8 > 60%

6.6b

5 > 75%
10 > 60%

CASE C-3
(6VL)
10.5/5.5
P(R < 5RSS) = 29

Fig. 6.6

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8-2

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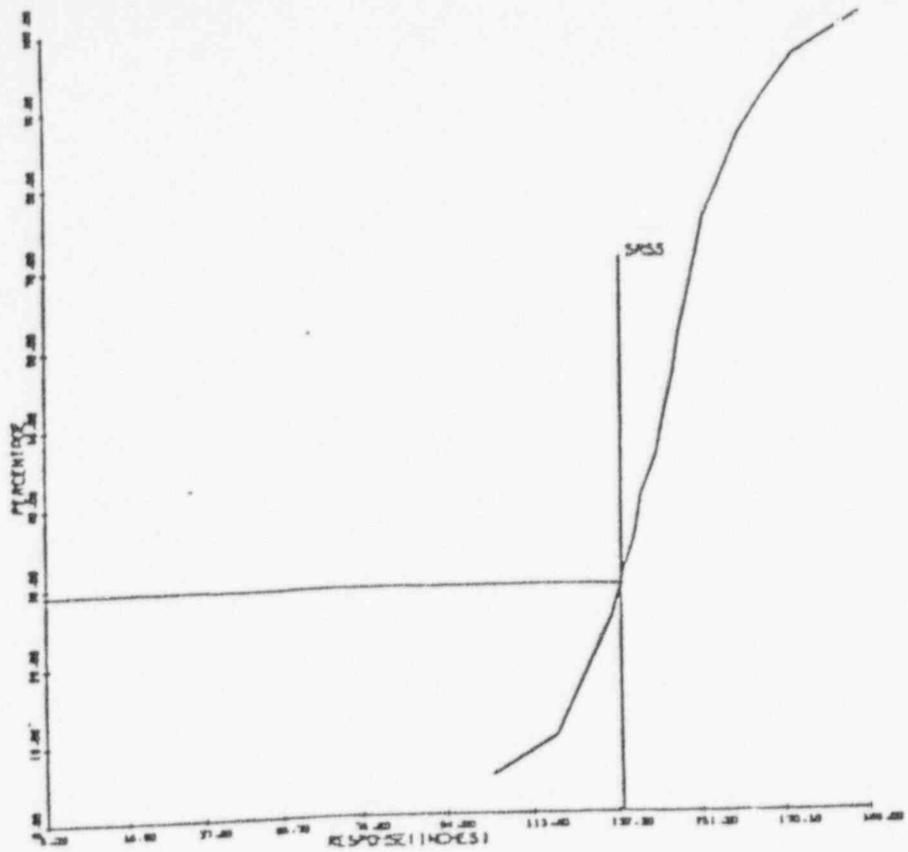
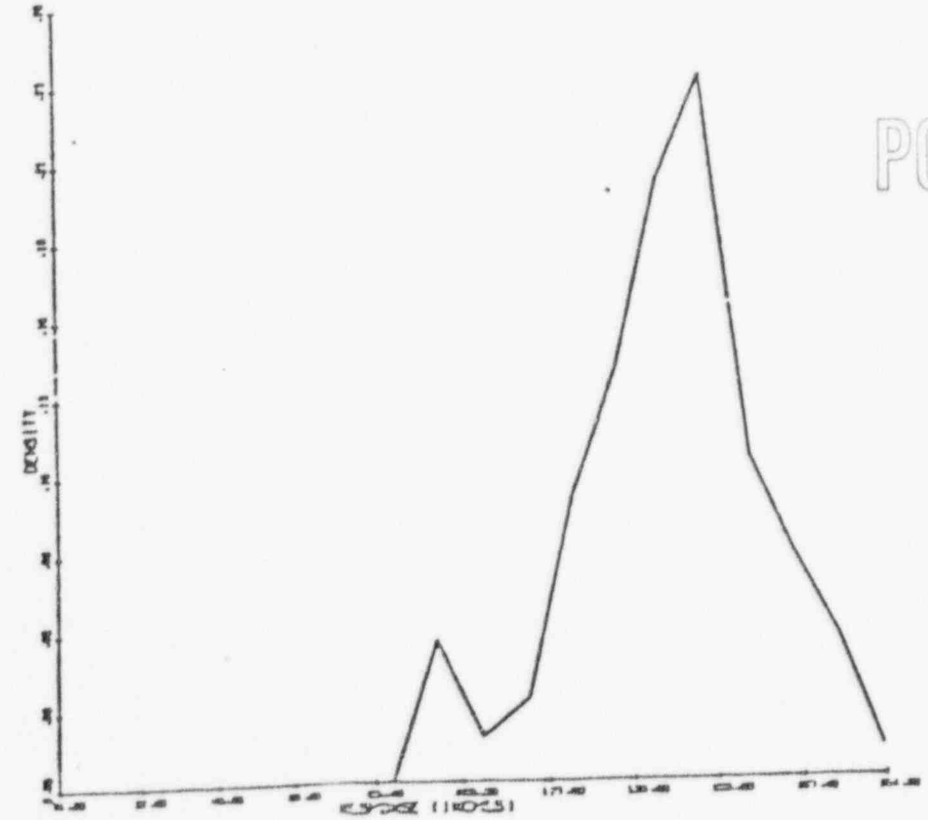


CASE C-3 FREQ:6.12 SIGMA=5.5 DUR=10.10.

29%

6.6c



CASE C-3 FREQ=6.12 SIGMA=5.5 DUR=10.10.

POOR ORIGINAL

6.6d

CASE C-
(cont)

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(d) Peaks which are less than 60 percent but greater than ± 45 percent may also play a role in influencing the SRSS rule.

(e) In carrying out the Monte Carlo computation, results show that in some cases even if the peak count satisfies the criterion, the non-exceedance probability of SRSS falls below 50 percent.

6.6 Effect of Non-Zero Mean

To investigate the extent to which departures from zero mean affect the acceptibility of criterion 1, Monte Carlo simulations were carried out. Figure 6.7 shows a LOCA response where the mean is not zero. The mean was measured as -0.06. This was combined with an SSE response in which the mean is also negative (-0.13), as shown in Figure 6.8. The combined result for this case shows the P(R < SRSS) at 48 percent. Table 6.2 lists this result as Case 4. This is the lowest result in the table because the non-zero mean has been combined with the dynamically varying portion in a square root of the sum of the squares procedure. Actually, when a response is constant with time it should be added to a dynamic signal as the absolute sum rather than as the square root of the sum of squares. When this is done, the 48 percent of Case 4 for the P(R < SRSS) is increased to 70 percent. The other Monte Carlo simulations in Table 6.2 confirm this and show that the following formula can be used:

$$SRSS = \Sigma|\mu_i| + \sqrt{\Sigma(R_{imax} - \mu_i)^2}$$

where μ_i and R_{imax} are the mean and maximum values of individual response components. For cases involving varying zero mean, however, a procedure still needs to be defined since the above expression would not be applicable as it stands.

6.7 Effect of Differences in Response Signal Duration

The meaning of variation of response duration time needs to be clarified.

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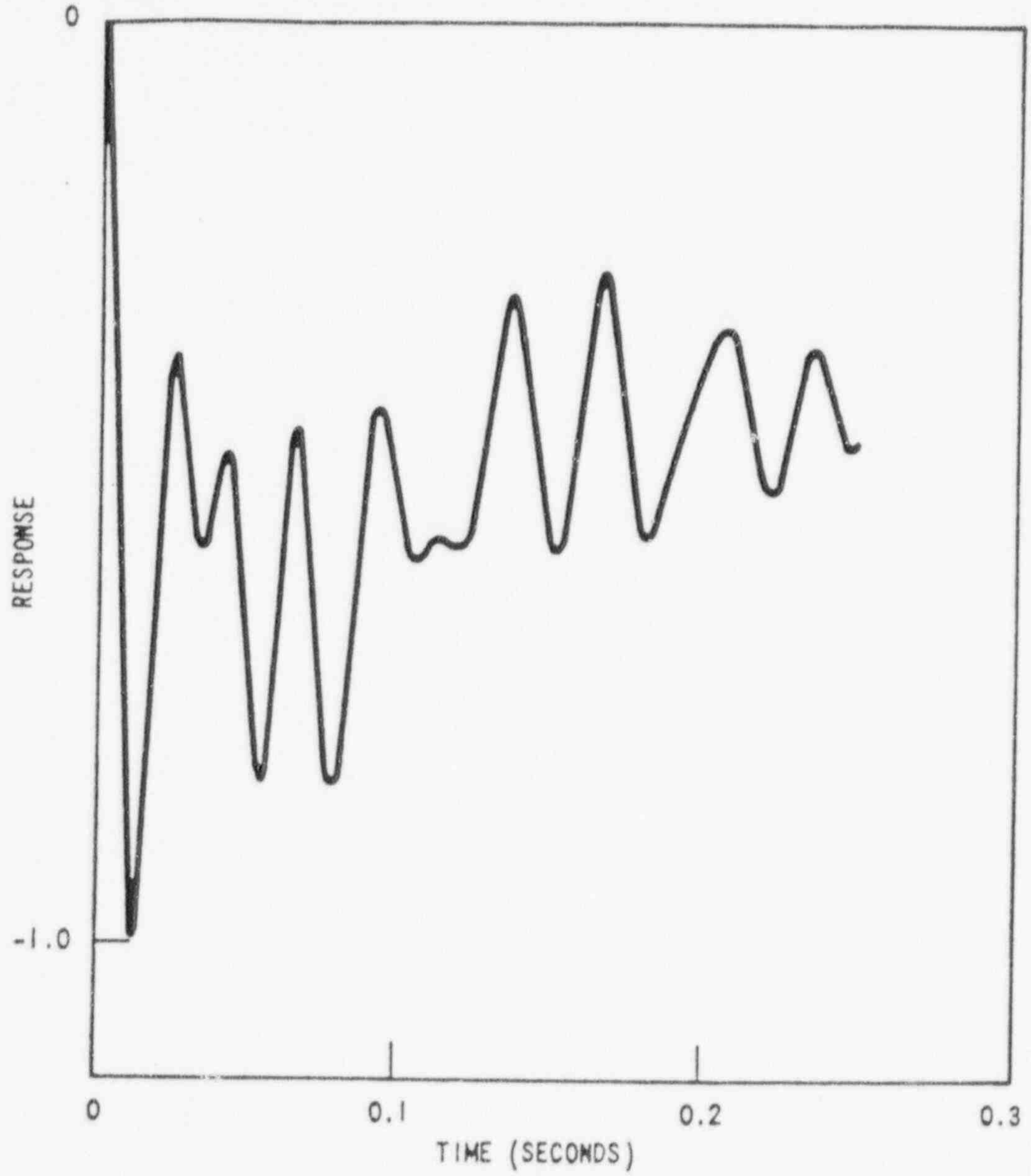

Fig. 6.7 LOCA Response Number 25

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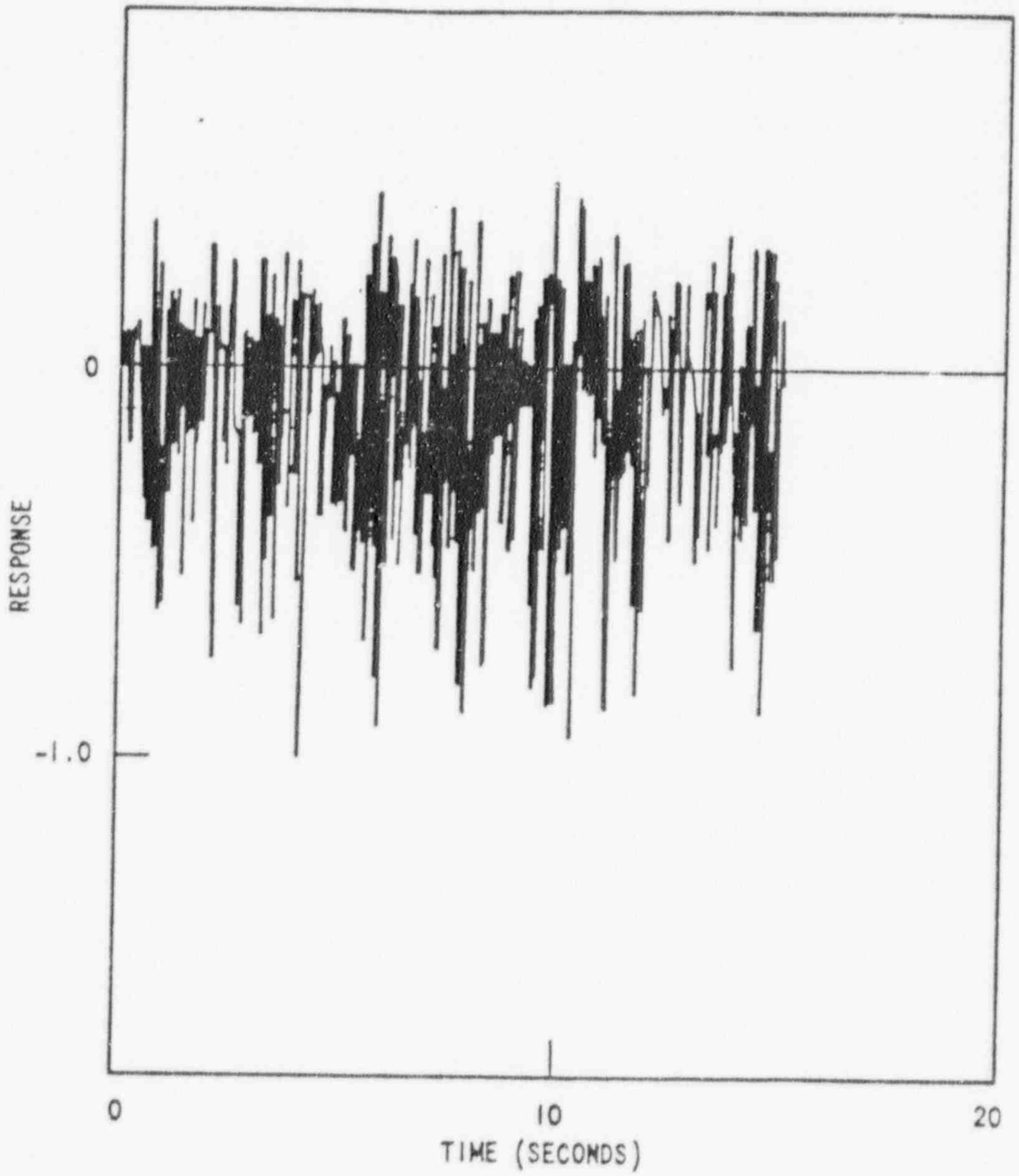

Fig. 6.8 SSE Response Number 25

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TABLE 6.2

Responses With Non-Zero Mean

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CASE NO.	RESPONSES	SOURCE	P(R ≤ SRSS)	REMARKS
1	LOCA NO. 22 SSE NO. 22	W	.84	SKEWED + " 0
2	LOCA NO. 23 SSE NO. 23	W	.72	" + " +
3	LOCA NO. 24 SSE NO. 24	W	.98	" + " -
4	LOCA NO. 25 SSE NO. 25	W	.48	" - " -
5.	LOCA NO. 26 SSE NO. 26	W	.89	" + " -
6.	LOCA NO. 28 SSE NO. 28	W	.68	" + " 0
7.	LOCA NO. 29 SSE No. 29	W	.81	" + SPARSE " 0
8.	LOCA NO. 30 SSE NO. 30	W	.98	" - " + SPARSE
9.	LOCA NO. 31 SSE NO. 31	W	.98	" - " + SPARSE
10.	FIG. B-36 OBE FIG. B-37 SRV	G.E.	.71	SKEWED 0 0

W - WESTINGHOUSE
G.E. - GENERAL ELECTRIC

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Shorter duration could result in the elimination of either the insignificant portion of an original function or the significant portions of the signal. If significant portions of a response function are eliminated, resultant combinations could exhibit either higher or lower values.

The main influence factors are the exceedance probability distribution or σ/R_{max} values. The frequency content of the component responses also play a role in the resultant non-exceedance probability of SRSS. Table 6.3 shows some of the results. Compare, for instance, Case 2 with Case 8. In both cases, the center frequency is the same and the number of peaks is the same. However, the NEP of SRSS changes from 81% in Case 2 to 67% in Case 8. Note that the σ/R_{max} in Case 2 is 0.324 as compared to 0.350 for Case 8. Again, comparing Case 5 with Case 12. The number of peaks exceeding 75% and 60% of maximum is greater in Case 5 than in Case 12. Yet the NEP of SRSS is 78% for Case 5 (σ/R_{max} = 0.321) as compared with 67% for Case 12 (σ/R_{max} = 0.351). These are specific examples where the number of peaks by themselves do not define the non-exceedance probabilities completely. The amount of time that a peak exists, or the width of a peak, is also a factor. This is taken into account by the column σ/R_{max} since the σ is obtained from a digitized examination of the signal with respect to time.

Table 6.4 shows some specific cases in which one signal is held constant while the other signal duration is shortened. For all cases in the table, both signals have a frequency content which is randomly distributed.

The first signal is always the longer one. It has a center frequency of 4 Hz and a standard deviation of 3 Hz. The second signal has a center frequency of 12 Hz with a standard deviation of 3 Hz.

The second signal is shown as R_2 in figure 6.9a. The frequency composition is shown in Figure 6.9b with the average frequency at 12 Hz. Figure 6.9c

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TABLE 6.3

Comparison of Exceedance Probability Distribution with Different σ/R_{max} Values

Comb. No.	Comb. No.	CENT. FREQ (rps)	FREQ DEV (rps)	Dur. (sec.)	No. of Peaks > 75% max	No. of Peaks > 60% max	$\frac{\sigma}{R_{max}}$	Prob.(R_{comb} < SRSS)
1	1 2	8 8	1 1	10 10	7 7	20 20	.325	.88
2	1 2	8 8	3 3	10 10	8 8	24 24	.324	.81
3	1 2	8 8	5 5	10 10	7 7	22 22	.319	.76
4	1 2	6 6	1 1	10 10	8 8	18 18	.281	.91
5	1 2	6 6	3 3	10 10	11 11	23 23	.321	.78
6	1 2	6 6	5 5	10 10	6 6	23 23	.321	.78
7	1 2	8 8	1 1	10 5	7 9	20 28	.325 .352 .378	.81
8	1 2	8 8	3 3	10 5	8 8	24 24	.323 .350 .375	.67
9	1 2	8 8	5 5	10 5	7 13	22 24	.319 .358 .394	.62
10	1 2	6 6	1 1	10 5	8 8	18 18	.280 .288 .296	.88
11	1 2	6 6	3 3	10 5	11 9	13 21	.319 .343 .366	.68
12	1 2	6 6	5 5	10 5	6 11	23 22	.321 .351 .379	.64
13	1 2	6 12	1 1	10 10	8 15	18 36	.281 .317 .350	.59
14	1 2	6 12	3 3	10 10	11 4	23 20	.321 .318 .315	.77
15	1 2	6 12	5 5	10 10	6 13	23 36	.321 .342 .362	.68

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TABLE 6.4

Duration Effects on Non-Exceedance Probability

a) Effect of Reducing Duration of Response 2

Case No.	Comp. No.	Center Freq	Freq Dev.	Duration	P(R < SRSS)
1	1	4	3	8.5	34%
	2	12	3	4.3	
2	1	4	3	8.5	39%
	2	12	3	3.8	
3	1	4	3	8.5	40%
	2	12	3	3.4	
4	1	4	3	8.5	42%
	2	12	3	3.2	
5	1	4	3	8.5	44%
	2	12	3	3.0	
6	1	4	3	8.5	52%
	2	12	3	2.8	

b) Effect of Reducing Duration of Response 1

Case No.	Comp. No.	Center Freq	Freq Dev.	Duration	P(R < SRSS)
7	1	4	3	11.0	40%
	2	12	3	4.5	
8	1	4	3	9.5	30%
	2	12	3	4.5	
9	1	4	3	9.0	31%
	2	12	3	4.5	
10	1	4	3	8.5	28%
	2	12	3	4.5	

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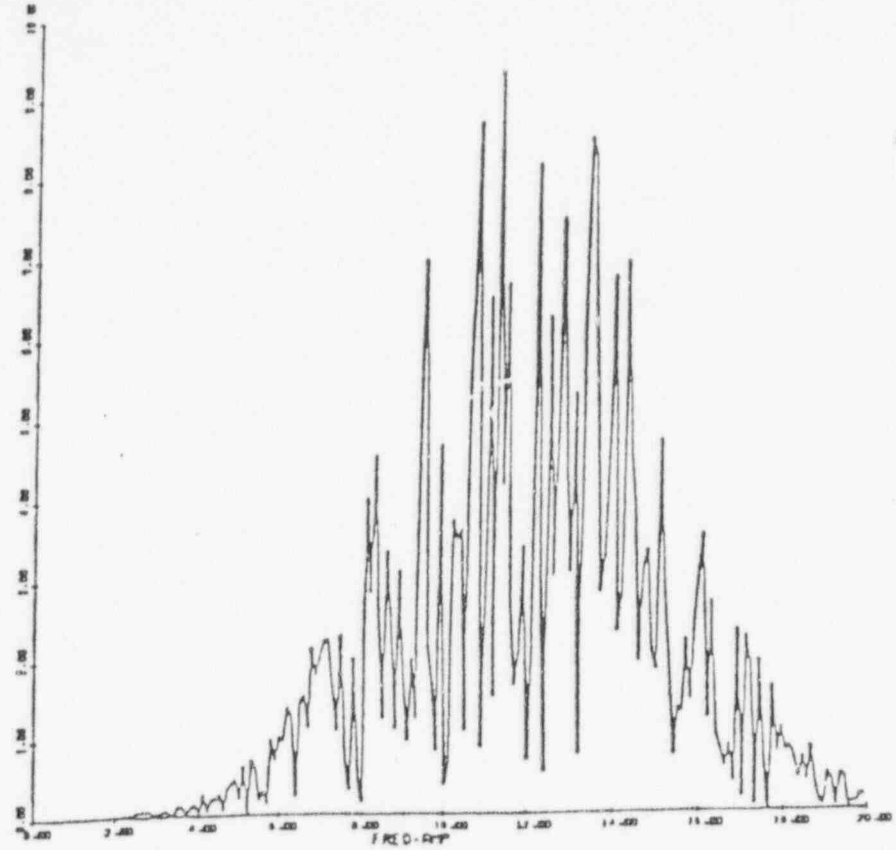

Fig. 6.9(b). Frequency Content for Response in Fig. 6.9(a)

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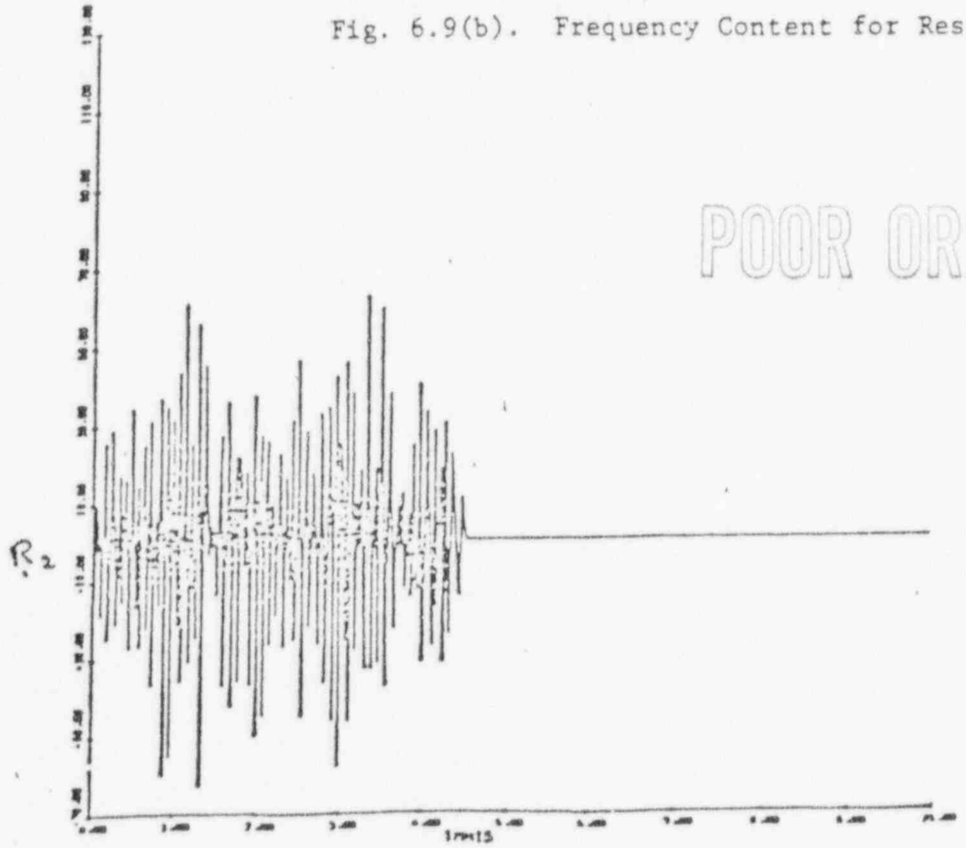

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Fig. 6.9(a). Response Component to Study the Effect of Response Duration

CASE D-1
(OHA)
8.5/4.5

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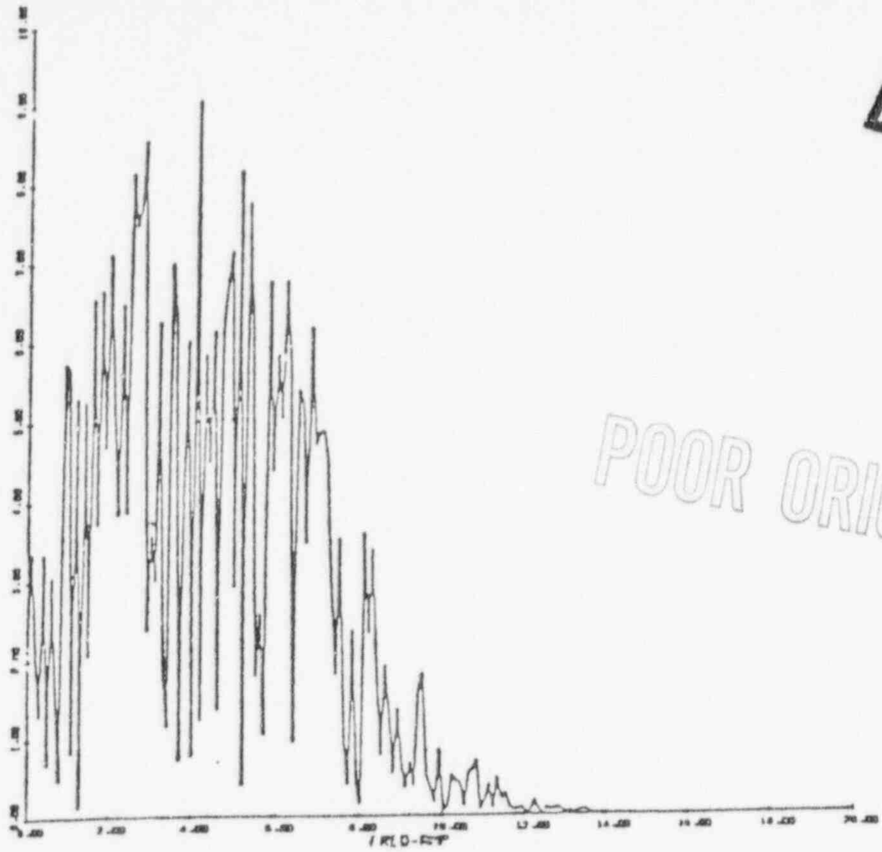
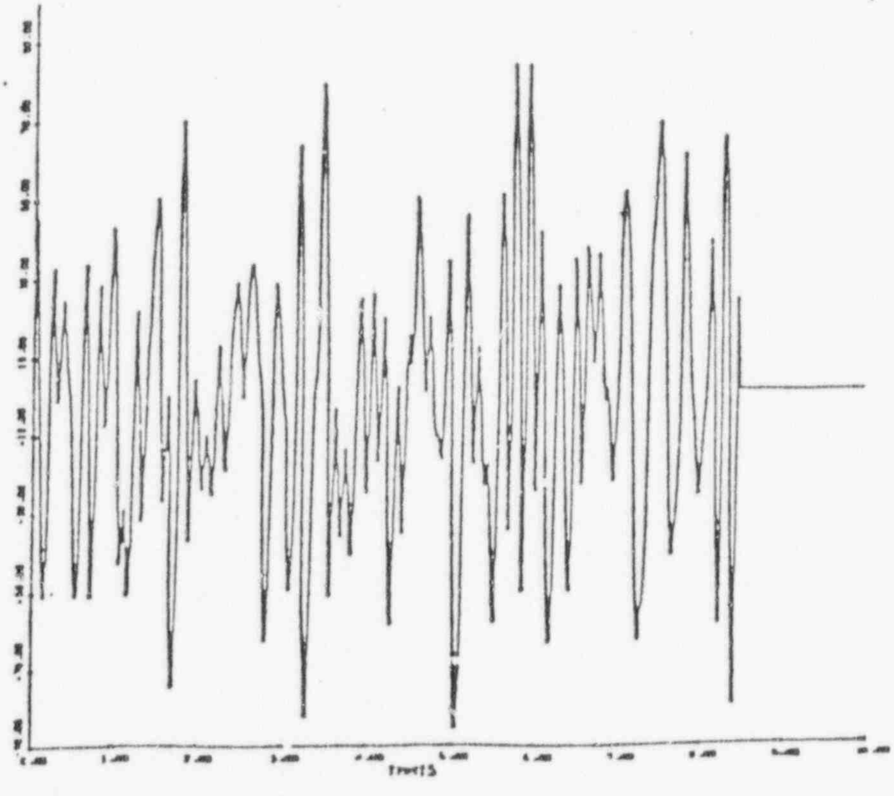
POOR ORIGINAL



CASE C-5 FREQ:4.12 SIGMA:3.3 DUR:10.10.

Fig. 6.9(d). Frequency Content for Response in Fig. 6.9(c)

R_1



CASE C-5 FREQ:4.12 SIGMA:3.3 DUR:10.10.

CASE D-1
(OHA)
8.5/4.5
P(R < 5R55) = 2E

Fig. 6.9(c). Response Component to Study the Effect of Response Duration

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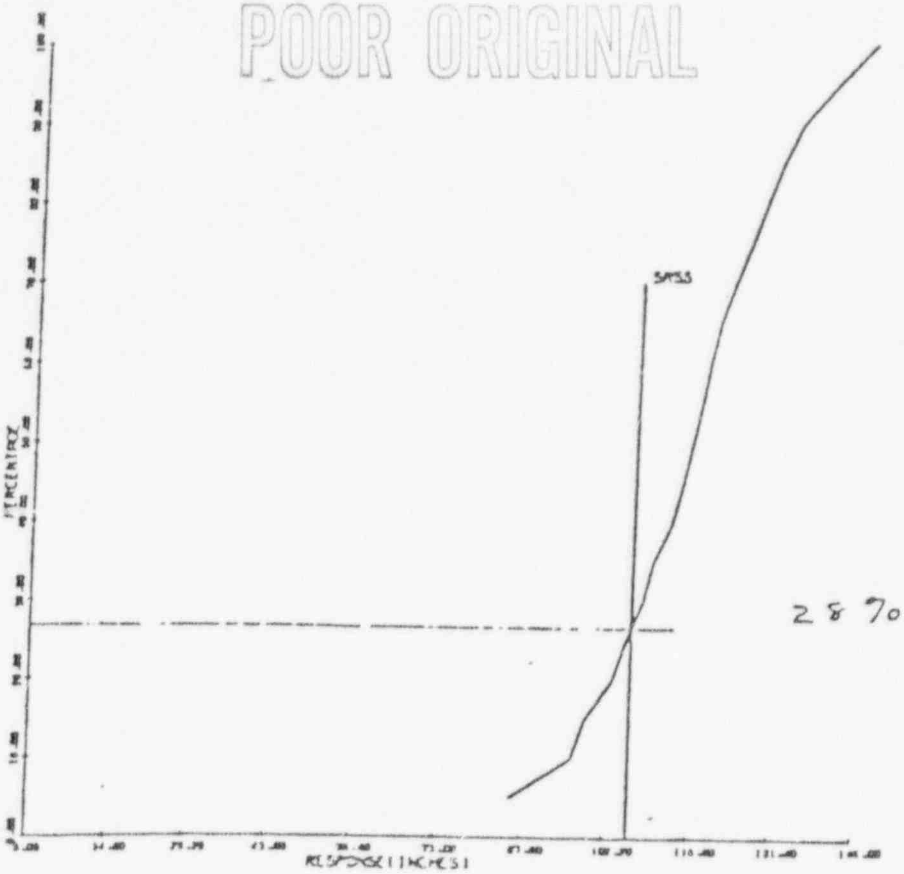
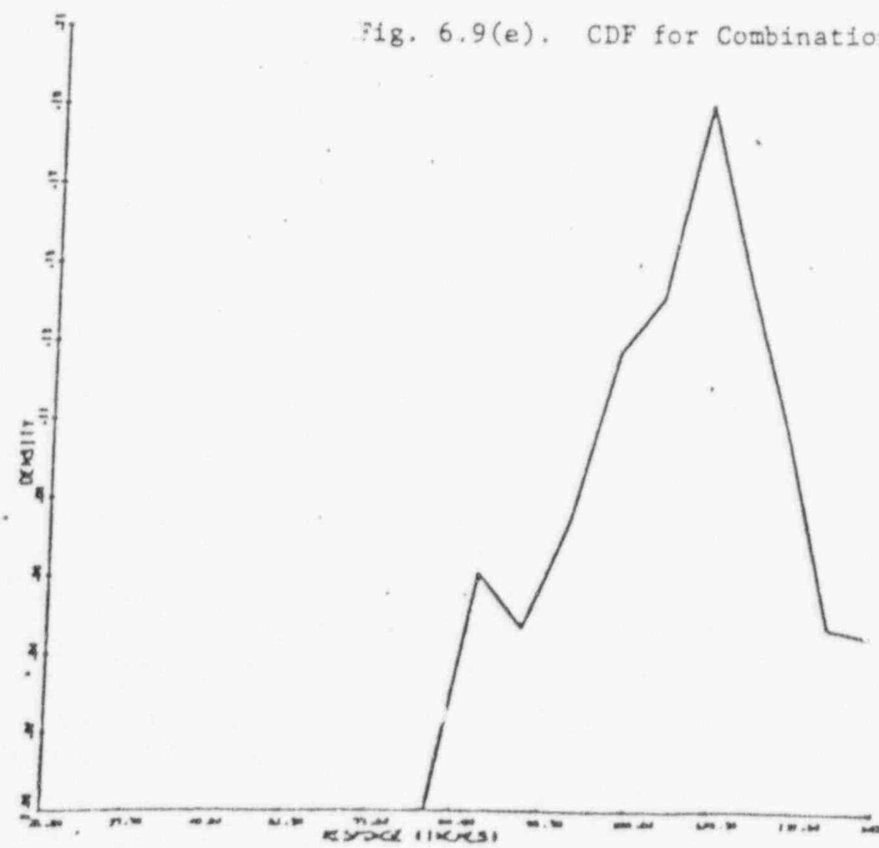


CASE E-5 FREQ=4.12 SIGMA=3.3

Fig. 6.9(e). CDF for Combination of Response



CASE E-5 FREQ=4.12 SIGMA=3.3

Fig 6 9(f)

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CASE D-1
(OMA)
8.5/4.5

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shows the first signal, R_1, with a duration of 8.5 seconds and the correspond-ing spectrum is in Figure 6.9d. The cumulative distribution function (CDF) has the SRSS plotted on the curve. This is shown at 28% in Figure 6.9e. The last figure in the group, Figure 6.9f shows the probability density function for Case 10.

For Table 6.4(a), the first signal is held constant at 8.5 seconds while the second signal starts out at a value of 4.3 seconds. for the cases 1 through 6, the second signal is progressively decreased from the 4.3 seconds to 2.8 seconds. As this is done, the NEP of SRSS increases from 34% for the longer duration of the second signal to 52% for the shorter duration of the second signal.

In Table 6.4(b), the second signal is held constant at 4.5 seconds while the first signal is decreased. Case 7 shows that the duration of the first signal is 11.0 seconds. The duration of the first signal is then successively reduced to 8.5 seconds in Case 10. Table 6.4(b) also confirms the results of Table 6.4(a). This says that as the duration time of the second signal becomes smaller and smaller with respect to the first signal, the NEP of SRSS increases. Local changes that are contrary to this trend might occur because of the particular characteristics of the two signals, as is seen between Cases 7 and 8. However, the overall trend is that as one signal is very short with respect to the other, the chances for peaks to combine becomes less, hence the increase in the non-exceedance probability.

For this study, the duration of the first signal was increased by adding a portion with comparatively small magnitude. An example is shown in Figure 6.10a, Case 8, with the NEP of SRSS at 30%, as shown in Figure 6.10b.

6.8 Significance of Correlation Coefficients of Responses

The criterion of accepting a limiting correlation coefficient of 0.4 for SRSS methodology appears to have originated from the studies of combining

100

POOR ORIGINAL

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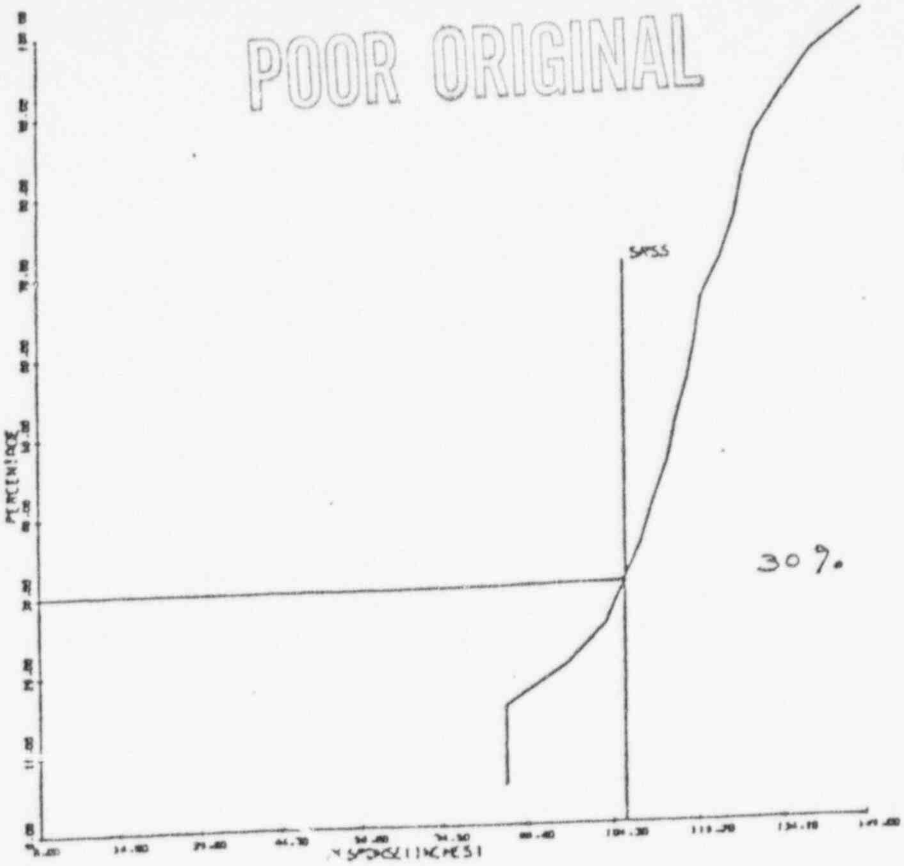
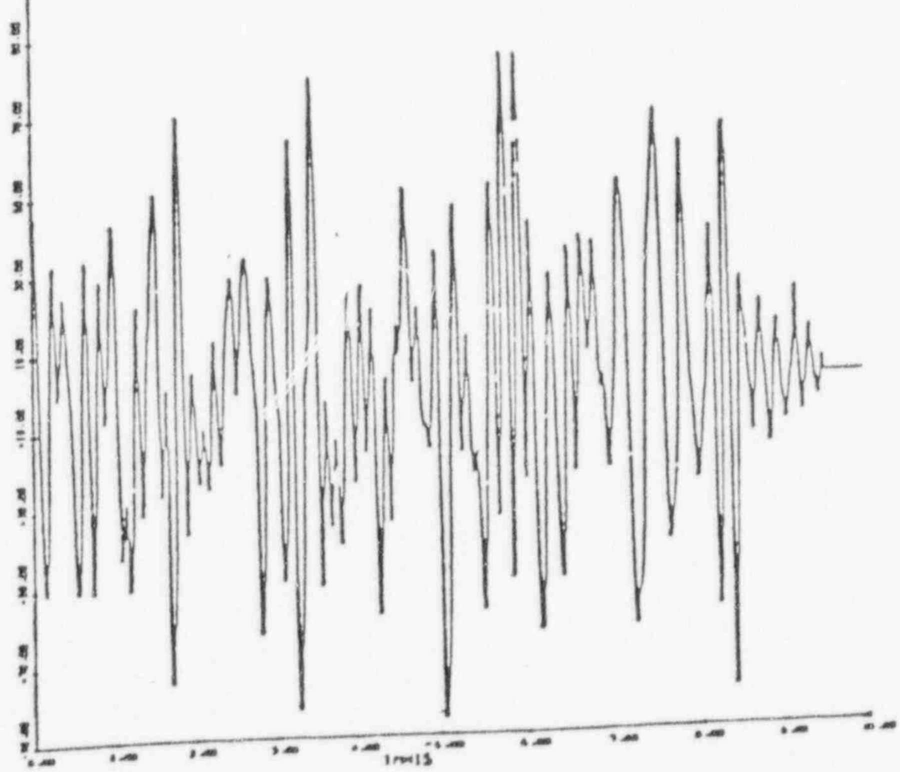


Fig. 6.1((b). CDF for Combination of Response

R_1



CASE D-3
(OHH)
9.5/4.5
P(R < SRSS) = 30

Fig. 6.10(a). Response Component to Study the Effect of Response Duration

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earthquakes in different directions where random time lag of responses is not considered. In the present case, when random time lags of component responses are the main considerations, the "original" correlation coefficient appears to be irrelevant.

Table 6.5 shows the relationship of the correlation coefficient of two original response functions and the non-exceedance probability of SRSS. To account for the time lag, the average correlation coefficient defined as $\rho = \frac{\Sigma\rho_\tau}{N_\tau}$ is also included in the table, where ρ_τ is the correlation coefficient at each time lag, and N_τ is the total number of lags used. The conclusions drawn from this investigation are that (a) the original correlation coefficient has no bearing on the SRSS rule based on random time lag, and (b) that the average correlation coefficient including time lag is small in all cases (< 0.25). A summary of each of the conclusion from all subsection of Section 6 is given in Section 1.6 of the introduction.

TABLE 6.5

Prob (R_{comb} < SRSS) Related to Correlation Coefficient

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Comb. No.	Comp. No.	P with τ=0	P_{γ} average	Prob(R_{comb} < SRSS)
1	1 2	1	.21	.88
2	1 2	1	.12	.81
3	1 2	1	.092	.78
⋮				
7	1 2	.27	.24	.81
8	1 2	.014	.13	.67
9	1 2	.045	.10	.62

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VII. REVIEW OF CRITERION 2

7.1 Background

When SRSS cannot be used to safely represent the combination result or when Criterion 1 cannot be used, an alternative approach is suggested by General Electric (G.E); namely, Criterion 2. This is accomplished by using the NEP on the CDF curve. Two salient factors must be determined to render the CDF reliable. The first factor involves the method of constructing the CDF, the second factor pertains to the acceptable NEP level. ~~This Section deals with the first factor.~~ The importance of both factors will be discussed in the sections that follow.

7.2 Method of Constructing Cumulative Distribution Function (CDF)

Recent literature has shown two distinct methods of constructing the CDF. The first method was employed by Brookhaven National Laboratory. In this method, for each sampling point (or each random time lag), the response at the digitized time points of the component signals were first algebraically combined to obtain the combined response history. Subsequently, the absolute value of the maximum peak is recorded as one sampling point. When adequate sampling points were obtained, the CDF curve was plotted automatically. This also appears to be the method used by Westinghouse in their report dealing with the response combinations.

The second method, employed by General Electric, is different from the first method in that it separates each component response signal into two parts, the positive part and the negative part. Thus for each sampling point, positive and negative parts of the component responses were combined separately. This results in two CDF curves and two SRSS values, one for the positive values, and the other for the negative values. It appears that the more conservative CDF curve obtained from either the positive or negative, was the one used by General Electric in their evaluations.

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In comparing the BNL and G.E. methods for constructing the CDF curves for evaluation the NEP of SRSS, we have found that the BNL method always results in a more conservative NEP of SRSS. Besides, the BNL method results a single unique CDF curve and thus no ambiguity will arise in its application.

7.3 Acceptable Non-Exceedance Probability (NEP) for the Combination Results

As regards the second factor, namely, the acceptable level of NEP on the CDF curve for determining the resultant response, there is a body of opinion especially among earthquake specialists, that the latter should be located approximately at mean-plus-one standard deviation (or 84% level), when all credible dynamic loads are considered. However, if the loads were already specified at a conservative value (say, at the level of mean-plus-one standard deviation), then the NEP level may be lower. This, essentially, is the basis of G.E.'s justification for Criterion 2.

It should be noted while this justification is probably correct, it requires a specific knowledge about the conservatism of the loads. As an example in the G.E. approach for justifying Criterion 2, a single signal (such as an earthquake or SRV resonse (not loads)) is simply multiplied by a randomly-generated factor prior to carrying out the combination procedure for determining the CDF. This procedure lacks such effects as the variation of amplitude with time and the variation of frequency content. As indicated in all of our previous studies, these factors can be of great importance in some instances. The cases where this takes on importance, however, is not at all obvious, nevertheless, based on our experience with Criterion 1, such probabilities do exist. Furthermore, even when one specifically knows that the loads used for the responses are conservative, and thus there is justification for accepting a lower NEP level than the 84 percentile, the question of "how much lower is acceptable" is still open to question.

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Because of the above questions, our approach in evaluating Criterion 2 has been somewhat different. Referring to the flow chart shown in Figure 7.1, we selected randomly, five different earthquake signals (typically shown in Figure 7.2) and generated five artificial SRV signals (typically shown in Figure 7.3). These were then used as input to the simple piping system, shown previously in Figure 6.1. The five earthquake responses and the five SRV responses of the system were then combined in a permutative sequence to produce a global CDF (R_{A+T}) where amplitude and time lag are both random as gotten from the 25 combinations. Next, we construct from the five earthquake responses, a response curve which has the 84 percentile level of the peaks at each particular time step. The same process is followed for the SRV responses, as shown on the right-hand side of Figure 7.1. These two 84-percentile level responses are now combined (with time lag) to yield a CDF denoted by R_{T84}.

Results from this procedure did not agree with those of G.E. The 84 percentile on the CDF of R_{A+T} was not equivalent to the 50% on the CDF of R_{T84}.

In re-examining our approach, we decided to add another step into the verification process. This involves adjusting the 84%-level response curves so that their absolute maximum peaks would come out to be at the exact 84 percentile of the absolute peak value of the five original response curves. In adjusting the maximum peak to this value, we also adjusted all the other peaks of the response by the same ratio. Results with this additional procedure are shown in Figures 7.4, 7.5, and 7.6. It appears, from these Figures, that 50% of NEP on the CDF of $R_{(T84)}$ occurs in the vicinity of 80% on the CDF of R_{R+A}. Based on these results, the criteria is essentially verified. This verification, however, cannot be considered "all conclusive," and is not sufficient to justify the criterion generically. As mentioned, there is no inherent or fundamental

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uniqueness in the method used in generating the final CDF curves for checking the criterion. Perhaps, another way to check the criterion would be to apply the randomness at the load level instead of the response level. This approach, again, points out the non-uniqueness of the checking process. Furthermore, with respect to the right-hand side of Figure 7.1, it should be noted that we used a specific type of signal; namely, one caused by a Safety Relief Valve Actuation (SRV), the characteristics of which are specific and not general. This type of signal usually has a short duration time with relatively few peaks, when compared to an earthquake signal. Obviously, a piping system excited by the SRV signal also has a short duration time and not many peaks. As discussed in the attached Appendix, dealing with the Review of SRSS Method for Combining Loads for Mark II Plants, this type of combination is a special case (i.e., a long time with a very short time response) which will result in high NEP of SRSS. Consequently, verification with this signal may not indicate general verification with a broad range of signals. This signal was chosen because of its availability. At the time of the study, we were simultaniously reviewing Criterion 2 and working with digitized data for Mark II plants. It would be desirable to examine Criterion 2 with more general types of response signals.

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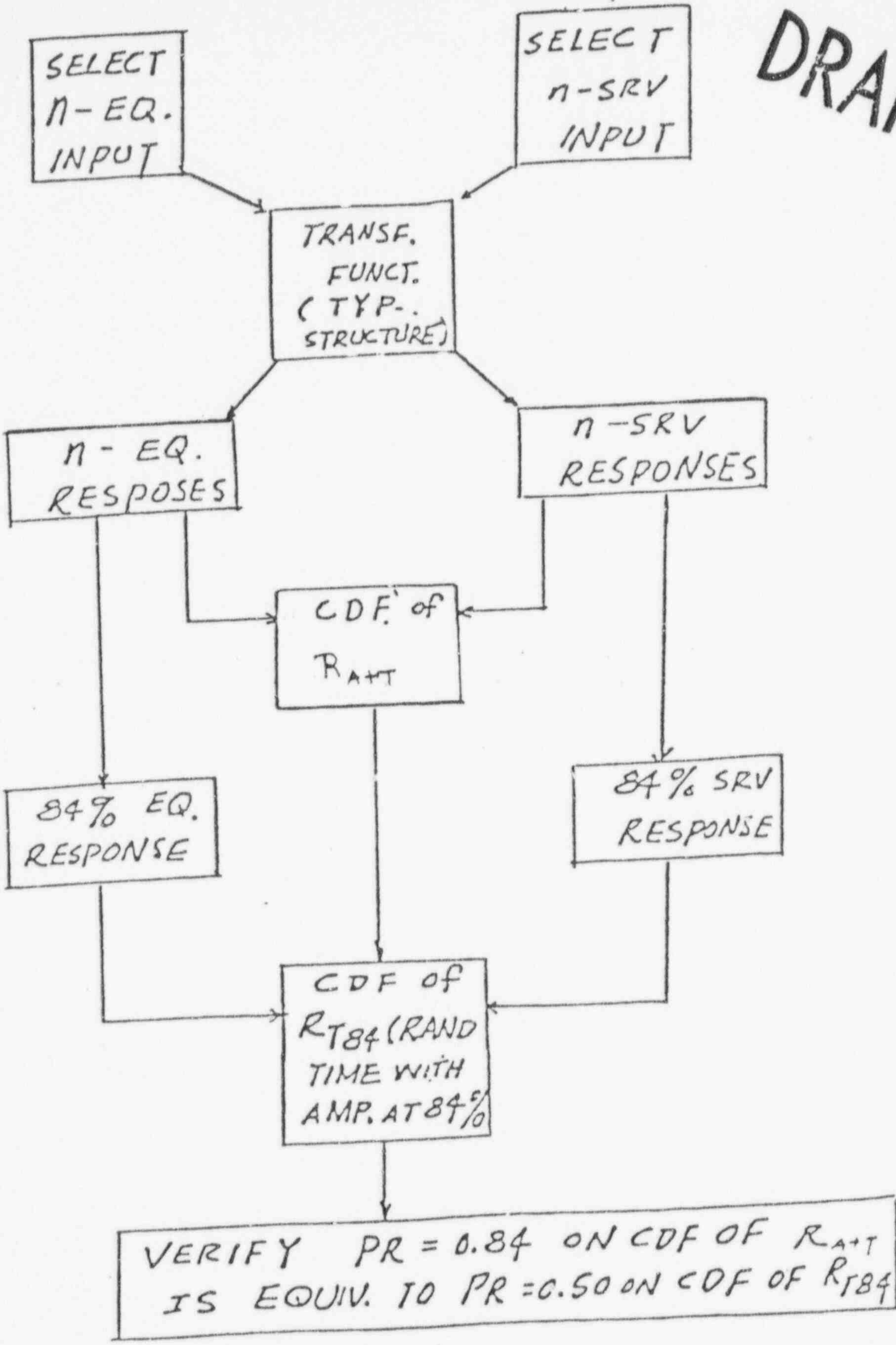

Fig. 7.1 Flow Chart of BNL Method for Evaluation of Criterion 2

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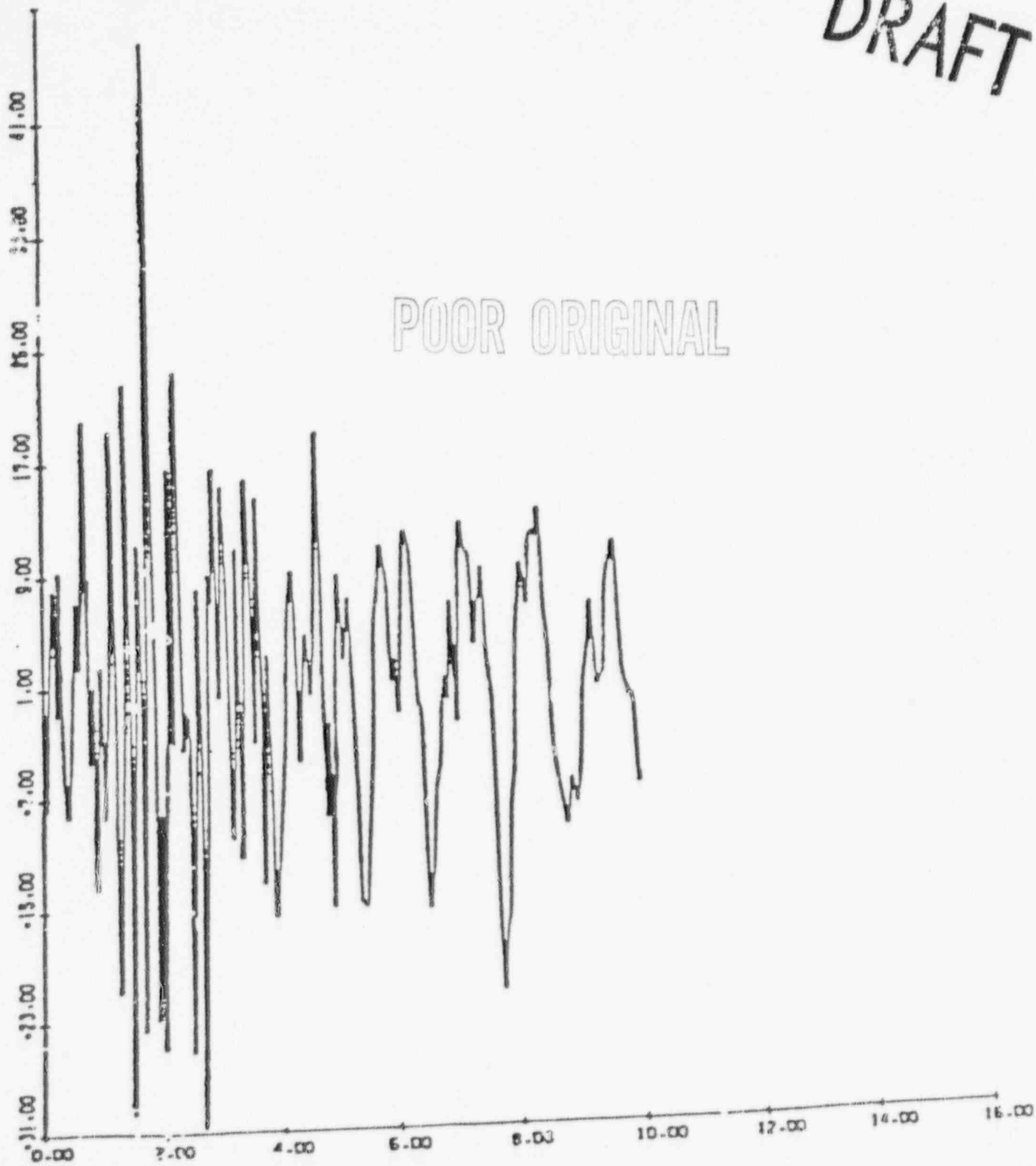

Fig. 7.2 Typical Earthquake Input.

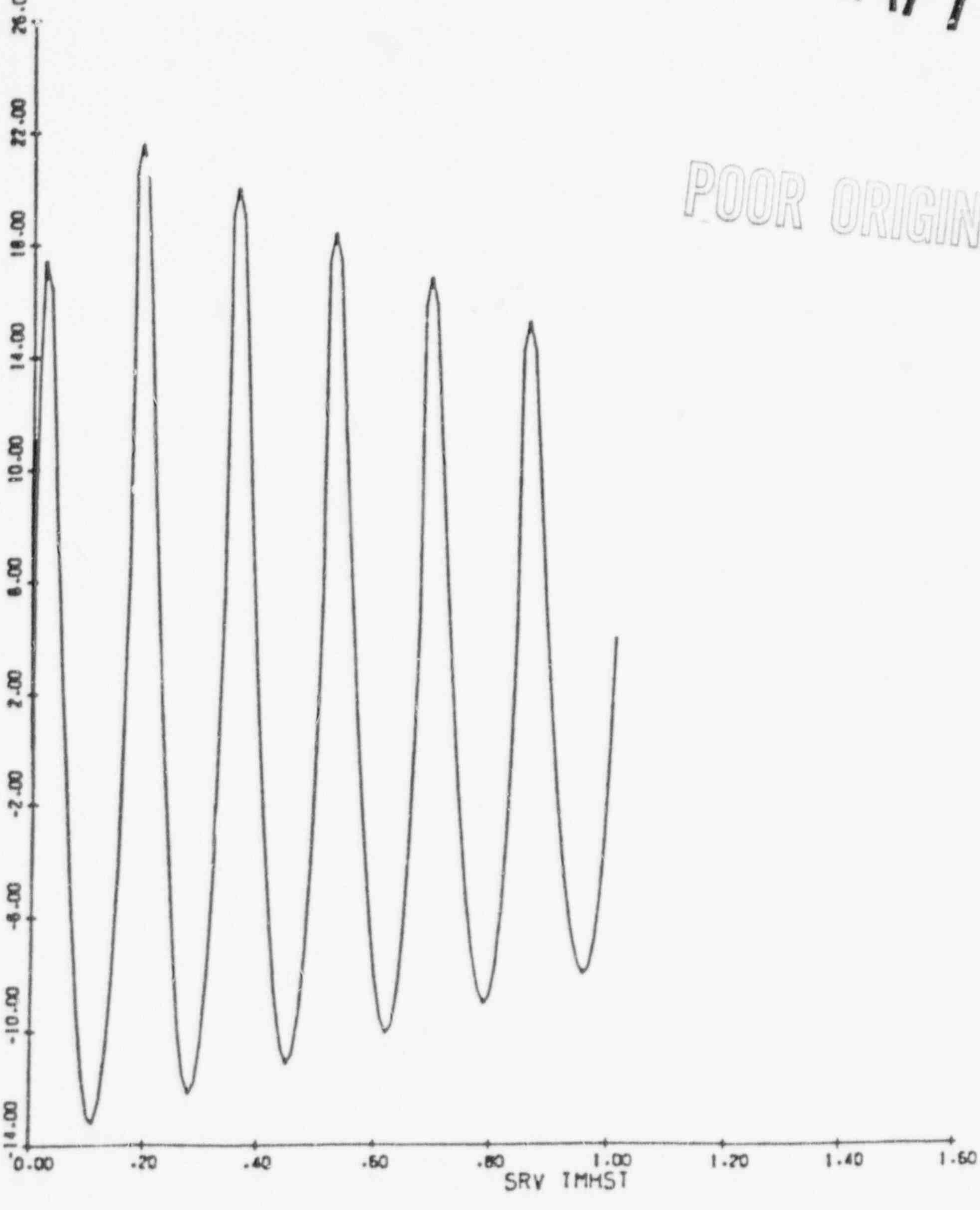

Fig. 7.3 Typical SRV Input

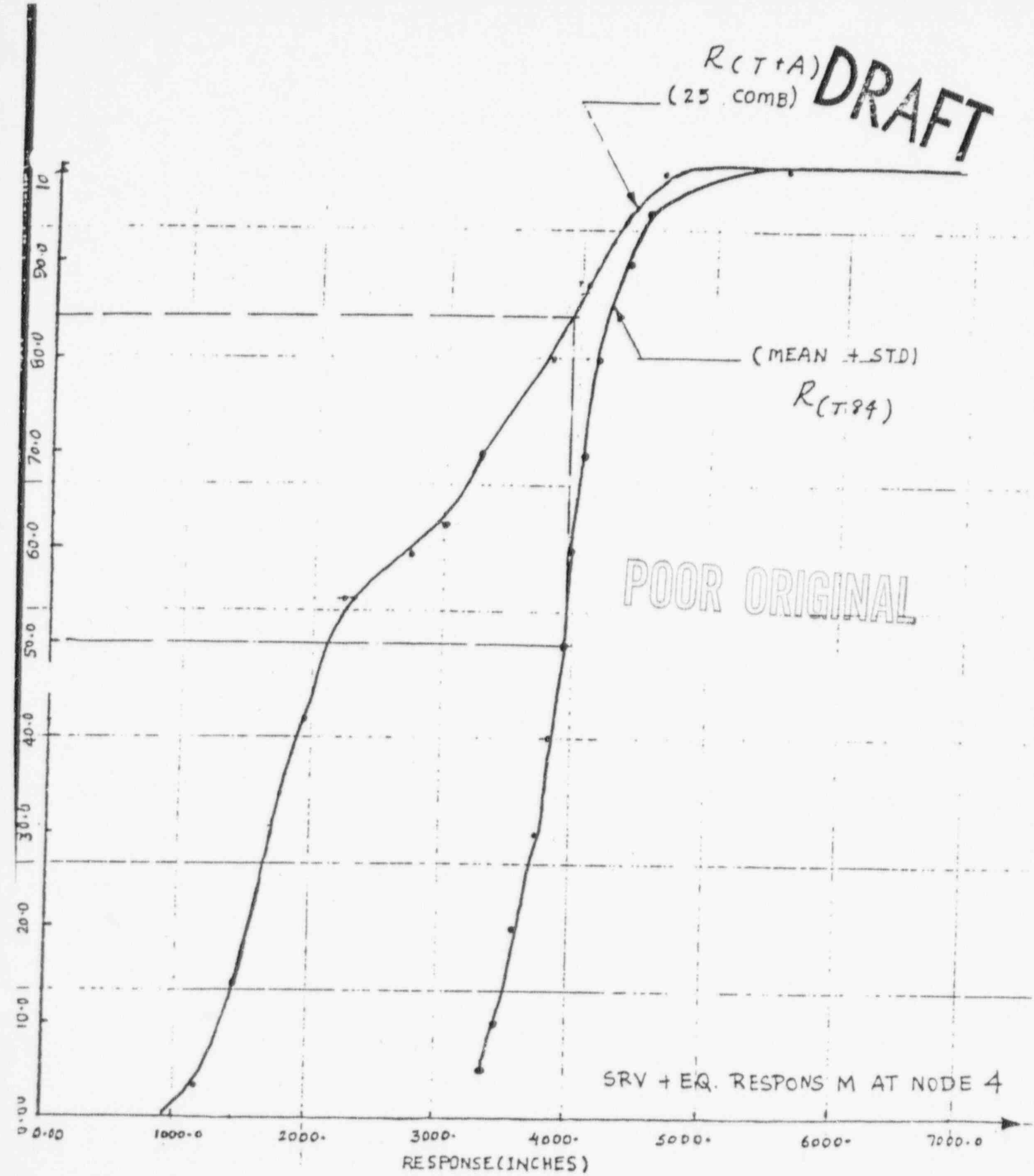

Fig. 7.4 CDF of R(T+A) and R(T84)

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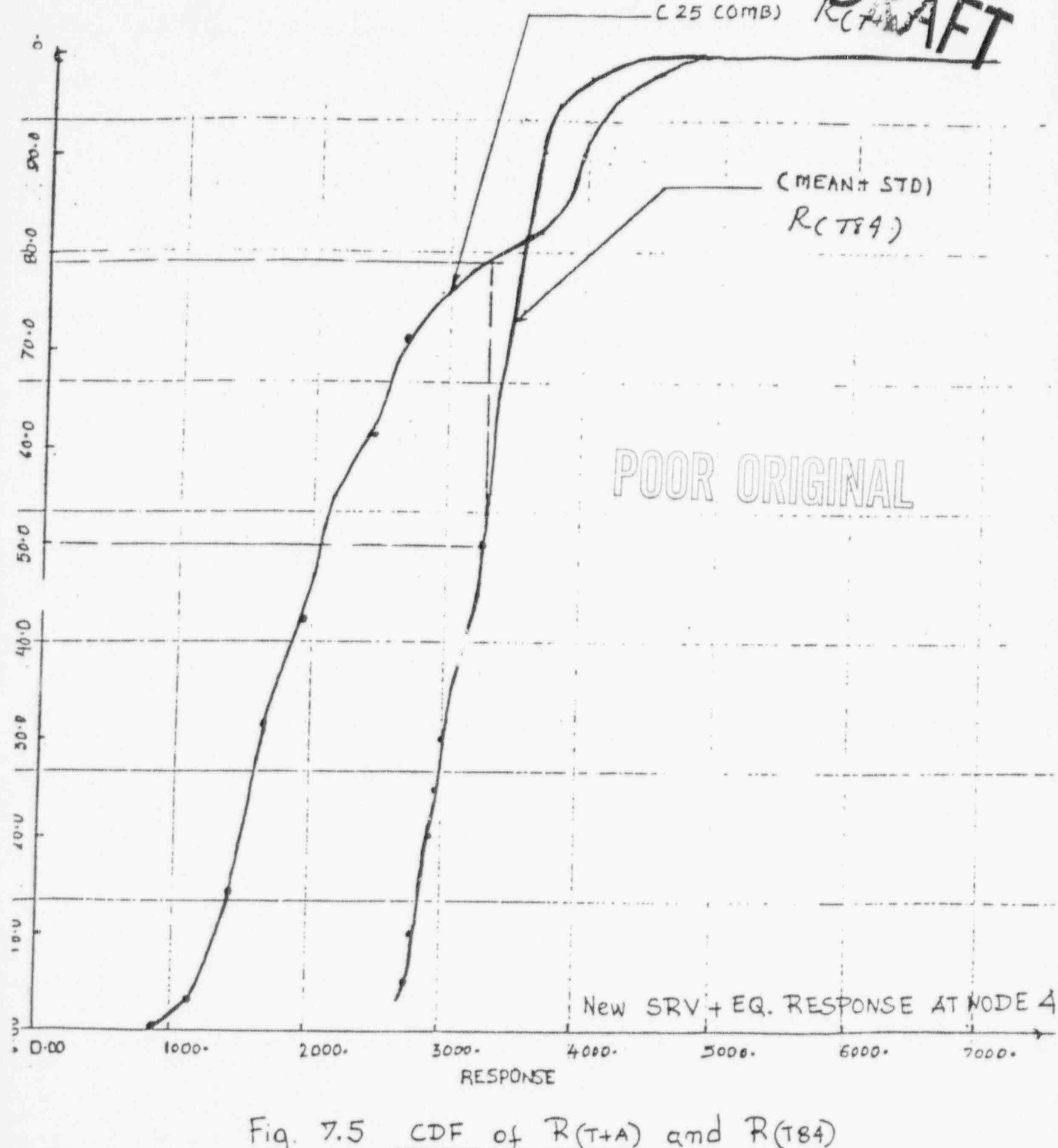

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Fig. 7.5 CDF of R(T+A) and R(T84)

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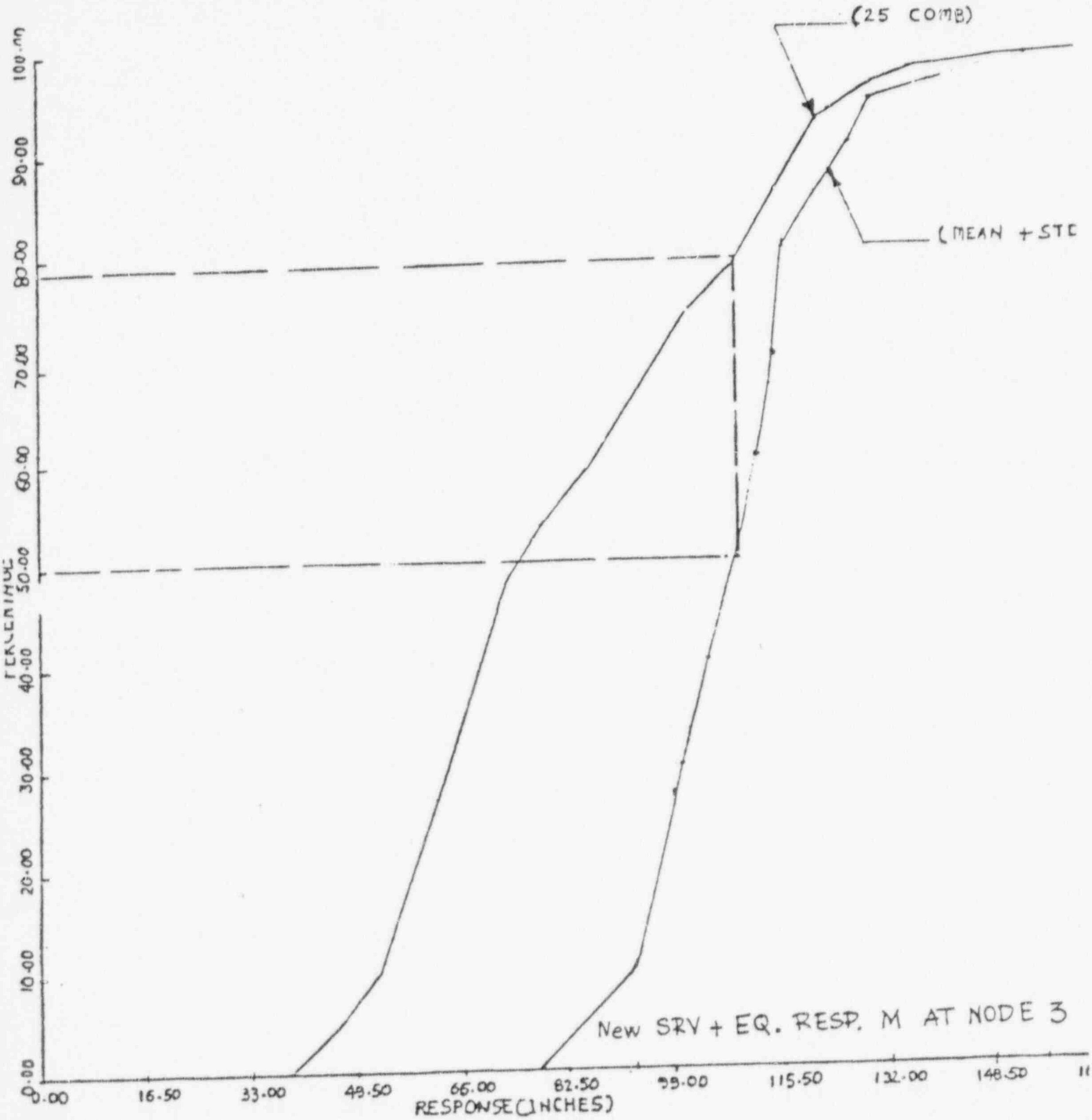

Fig 7.6 CDF of R(T+A) and R(T84)

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VIII. RECOMMENDATIONS

8.1 Significance of Load or Response Characteristics on the Outcome Combination Results

The characteristics of dynamic loads applied to nuclear power plants are generally available to the designers. On the other hand, the response characteristics becomes available only after a time history dynamic analysis has been performed. Besides, many earthquake responses are obtained by response spectra and thus no response history will be available. From the designer's point of view, it is advisable to formulate a guideline to determine whether SRSS can be justified when based solely on the characteristics of the load function. On the otherhand, from our generic studies, it was found that response characteristics could differ drastically from the load characteristics. By only considering the load characteristics the validity of using SRSS may not be justified with absolute confidence. The basic approach should still be based on the response characteristic. As an alternative for practical application, a limited but sufficient demonstrative type of dynamic analysis may be performed to establish the general trend with respect as to the applicability of the SRSS method for a specific problem of combination, say, such as earthquake and SRV.

8.2 Suggested Criterion for Dynamic Response Combinations

Since the simplified criterion of counting peaks of individual responses may not be sufficient for judging the applicability of the SRSS method and since the construction of CDF of the combined responses entails time-consuming computation two alternate criteria of combining dynamic response are suggested. These alternate criteria are based on the digitized response time histories. The time steps taken should be sufficiently small so that peak variations are adequately represented.

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This has the advantage in that both the width and height of the signal are considered. Thses two criteria were plotted as Fig. 8.1 and 8.2 based on data obtained from all our studies presented in the previous sections.

Specifically the criteria are:

(1) Based on the exceedance probability distribution of induvidual component response functions, and

(2) On the ratio of standard deviation of maximum response of individual component response function (σ/R_{max}). When combining two or more (n) different responses, (σ/R_{max}) may be computed as:

$$\frac{1}{\sqrt{n}} [\sum_{i=1}^{n}(\sigma_i/R_{i,\ max})^2]^{1/2}.$$

The criterion suggested in (1) is a qualitative evaluation of the validity of SRSS method. In applying the criterion, the exceedance propability of the individual response $\left(P(R>\gamma \cdot R_{max})\right)$ histories can be plotted and superimposed on Fig. 8.1. Suppose that the acceptable NEP of SRSS is .84 then if the plotted curve falls on or below the curve for $P(R \leq SRSS) = 0.84$ it indicates that SRSS is a valid combination result.

The criterion suggested in (2) is also qualitative in nature, but is somewhat easier to apply. In using this criterion, the digitized induvidual response data can be statistically analyzed to obtain the standard deviation σ of the peak values. The ratio of the standard deviation to the maximum peak R_{max} (or σ/R_{max}) is then located on Fig. 8.2 as abscessa. If the acceptable NEP of SRSS is 0.84 with the acceptable (σ/R_{max}) equal to 0.29 then any value of (σ/R_{max}) that is less than 0.29 indicates that SRSS is a valid combination result.

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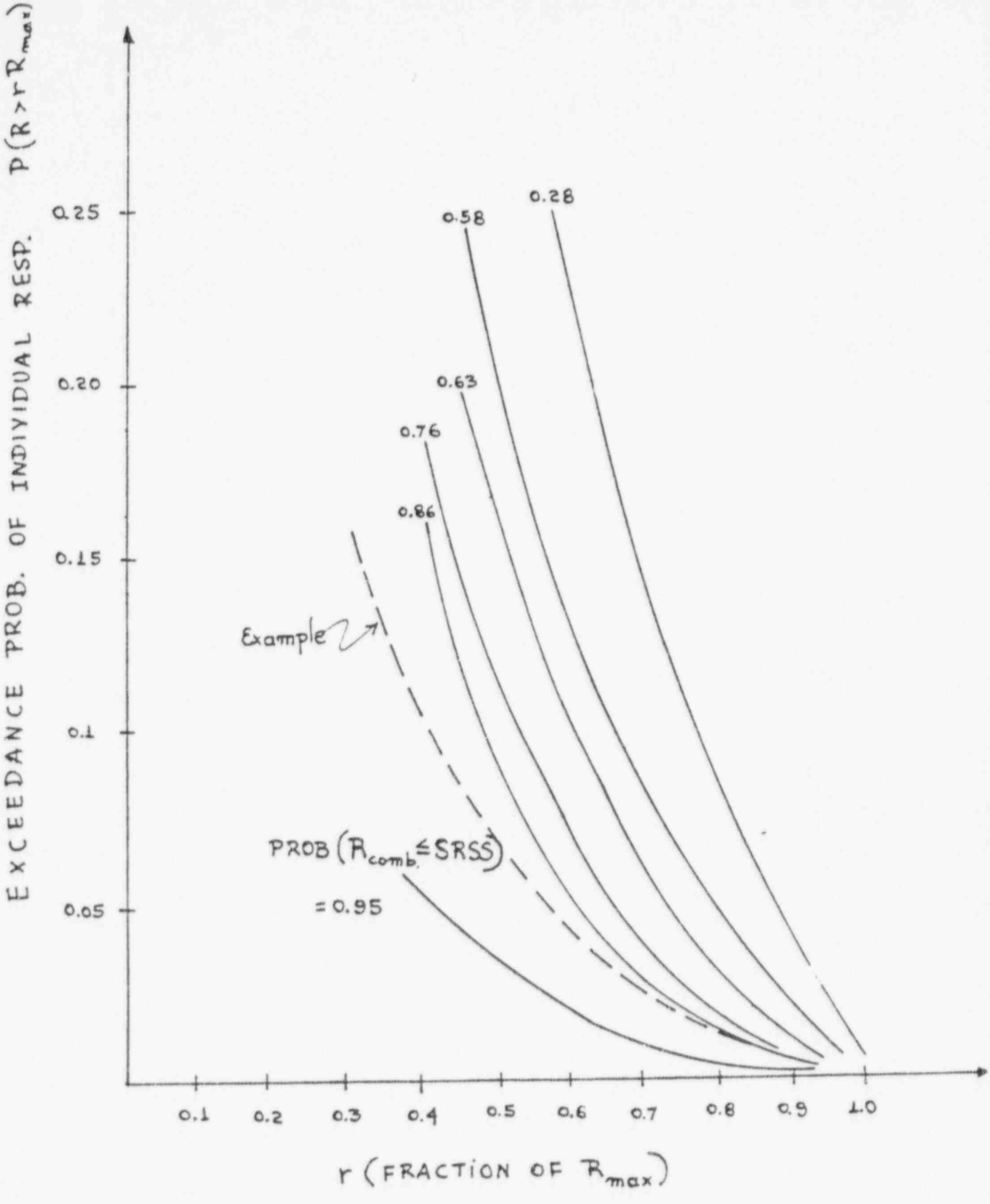

Fig. 8.1 PROB ($R_{comb} \leq$ SRSS) related to Prob. Dist. of Individual Resp.

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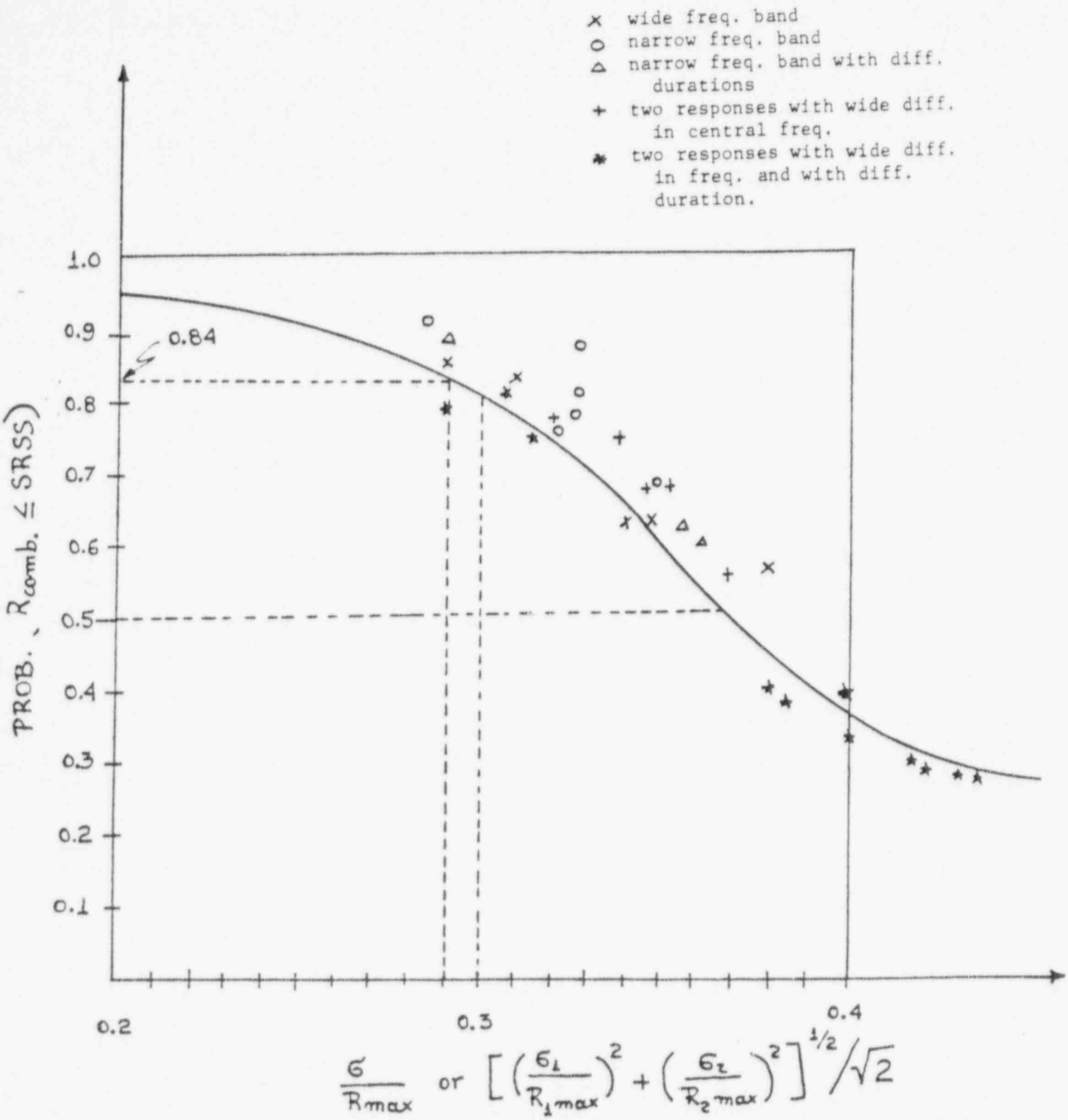

Fig. 8.2 PROB $(R_{comb.} \leq SRSS)$ related to $\frac{\sigma}{R_{max}}$

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APPENDIX A

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APPENDIX B

SUMMARY OF GENERAL ELECTRIC REPORT NEDO-24010-2

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