Comparative Study of Different Approaches for Aseismic Design of Mechanical Equipments

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Till now the dynamic analysis of earthquake loads of mechanical equipments in the Federal Republic of Germany was carried out exclusively with the help of deterministic methods. Presently for the evaluation of the system response the stochastic approaches are becoming more important. In this connection it is of importance to know the corresponding criteria applied for one or other method (deterministic or stochastic) as well as the different approaches applied for each group. These criterias should make it possible to consider the dynamic analysis on the one hand from the view of conservativeness and on the other hand from those like exactness, reliability and its relation to reality.

As a part of the consultative activities our company developed criteria for the evaluation of stochastic as well as deterministic analyses of vibration behaviour induced by seismic excitation at light secondary systems.

The important criterias leading to corresponding conclusions by deterministic methods are: Usefulness of the type of solution (time history, spectral method, etc.) the type of analysis (coupled or decoupled), type of connection between the primary and secondary system parts (number and position of the connecting points), type of combination of individual effects (support excitation points, modal components, earthquake spatial effects) and the order of combination (procedure sequence) used for all effects.

For the evaluation of stochastic methods and their results, the following criterias are of importance: Influence of system properties (fundamental frequency, distribution of frequency, damping values), type of idealisation of excitation (white noise with limited band width, approximation of the defined spectral density function by white noise, analytically defined spectral density), influence of nonstationarity (initial conditions, duration of excitation, damping, system behaviour).

Which type of method and mathematical model is to prefer regarding the reliability of the results when defined system properties and characteristic excitation values are given can be shown with the help of these criteria, their theoretical background and with the calculated results. The summarized consideration on the possibilities and boundary conditions of analytical approaches is made with respect to application and possible selection of stochastic methods in comparison with the usual deterministic approaches.

For the application of stochastic methods on earthquake problems, case to case decision is necessary regarding the choice of the mathematical model in connection with the reliability of the results, the character of the excitation and the properties of the systems.

The reason that from the random vibration analysis of equipment exact results to that from response spectra method are obtained, lies in the better consideration of modal couplings of the closely spaced modes of the systems and in the direct recording of the excitation through actual frequency components by the spectral density function. In no case the conclusion can be drawn that the deterministic methods lead to unusable results because they are conservative in most cases.

The stochastic procedure delivers on the other hand additional statements on the probability distribution of the structural response and on the estimation of the probability of exceeding a definite and unpermitted limiting value of the system response.

1. Introduction

The consideration of suitable safety for mechanical equipments in case of earthquake load has an important role in the licensing of nuclear power plants. Until now dynamic analyses of mechanical equipments in the Federal Republic of Germany were carried out exclusively with the help of deterministic methods. Presently for the evaluation of the system response the stochastic approaches are becoming more important.
In the present paper the methods (deterministic and random vibriations approaches) available for earthquake analyzing of mechanical equipments are considered and the limitations and advantages of each method are assessed.

2. Analytical Methods for Mechanical Structures

A general survey of analytical approaches currently being used for the seismic analysis of mechanical structures are outlined and discussed briefly in this chapter. The selection of an approach suitable to the problem under consideration is dependent on many factors. In this connection it is of importance to know the corresponding criterias applied for one or other methods (deterministic or stochastic) as well as the different approaches applied for each group. These criterias should make it possible to consider the dynamic analysis on one hand from the view of conservativeness and on the other hand from those like exactness, reliability and its relation to reality.

2.1 Deterministic Approaches

The important criterias leading to corresponding conclusions by deterministic methods are: Usefulness of the type of solution (time history, spectral method, etc.), the type of analysis (coupled or decoupled), type of connection between the primary and secondary system parts (number and position of the connecting points), type of combination of individual effects (support excitations points, modal components, earthquake spatial effects) and the order of combination (procedure sequence) used for all the three effects (Fig.1).

The modal superposition time history and modal superposition response spectras methods (with single or multiple input) are commonly used for dynamic analysis of structural systems subject to earthquake loading. This methods in their usual form, are applicable only to linear or linearized systems with energy loss mechanism represented by proportional damping. Briefly, these methods consist of determination of natural frequencies and mode shapes for the undamped system, transformation of the original coupled equations of motion for the physical coordinates to the decoupled equation of motion in terms of the normal coordinates, solution of the decoupled equation and finally, computation of the needed response quantities such as physical coordinates, absolute accelerations, bending moments, stresses, etc.. If the earthquake motion is specified as a function of time, a time history solution for the normal coordinates and the response quantities of interest can be obtained.

The analysis then consists of a time integration of the equation of motion by applying a convolution integral, by a step-by-step numerical intergration or by the Fourier transform method.

If the earthquake motion is specified in the form of its response spectrum, one can directly compute the peak values of the normal coordinates and the response quantities for each mode.

The peak quantities for individual modes can be combined to obtain the representative maximum value the responses using procedures such as those given in Regulatory Guide 1.92 /1/.

The single response spectrum method is limited to the use of one response spectrum which can be either an amplified spectrum enveloping the response spectra of all anchor points or the spectrum at the highest (or worst) elevation. The phase and amplitude relationship between the supporting points are not retained in the enveloped or worst spectrum approach. Therefore, for a complex system supported at different structural elevations and at different walls in a building, loss of the phase information requires the introduction of conservative procedures. However, this method requires the least computation effort. The time history method permits the application of different excitations at each of the support points; thereby enabling the problem to be solved in a realistic manner. This method suffers from the disadvantage that the solution process is costly and time consuming for a long duration earthquake record. Also, the large amount of data handling at the input time history generation can be very cumbersome. Improved solution schemes such as the separation of primary and secondary components, the modal superposition technique and output consideration, etc. may be employed to reduce the computing time.

The multiple response spectrum method also takes the different support excitations into account and yet the computation effort required is comparable to the single response spectrum method. The multiple response spectrum method computes the maximum response for each natural vibrations mode and for each support point excitation. There are several ways to obtain the final maximum total response from each natural mode and each support response spectrum.

Comparisons are made among the single response spectrum, time history, and multiple response spectrum predictions. The time history method is predicting considerably smaller response than the single response spectrum method. This is mainly due to the fact that the phase and amplitude relations between the support excitations are faithfully retained in the time history method.

The multiple response spectrum prediction has been observed to compare favourably with the time history method prediction.

In view of the present accuracy versus computation effort comparisons among the three methods, the multiple response spectrum method is the most efficient method for the seismic analysis of a multiply supported structural system.

2.2 Random Vibration Approach

There are three primary advantages in using the power spectral density method. First, the earthquake record, which is a random vibration, can be handled with aid of statistical analyses. Random vibrations contain frequencies in continuous distribution over a wide range. Second, the earthquake time history can be evaluated in terms of its actual frequency components alone. This is not entirely the case in the method using response spectra, as the frequency content is contained there implicitly. The generated spectrum is the response of single degree of freedom system as function of its natural frequency and damping. Thus, in that method information as the frequency content of the forces entering

into a system is missing. The third important advantage lies in the convenience for handling seismic testing requirements. For the evaluation of stochastic methods and the results obtained from them, the following criterias are of importance: Influence of system properties (fundamental frequency, distribution of frequency, damping values), type of idealisation of excitation (white noise with limited band width, approximation of the defined spectral density function by white noise, analytically defined spectral density), influence of nonstationarity (initial conditions, duration of excitation, damping, system behaviour)(Fig.2)

The above mentioned criterias lead by stochastic methods, for example, to following conclusions: Influence of fundamental frequency and the damping of the system react on the system response in such a way so that when those parameters are relatively large - the response approaches strongly the stationary condition. This is often the case in the analysis of soil systems; also for moderate and small period systems (e. g. nuclear plant structures) for damping values above 5 %.

When mechanical equipment is involved or when damping values are very low (< 1 %), transient analysis will be required (Fig. 3).

The reason that from the random vibration analysis of equipment exact results to that from response spectra method are obtained, lies in the better consideration of modal couplings of the closely spaced modes of the systems (Fig. 4) and in the direct recording of the excitation through actual frequency components by spectral density function. It will be assumend here that the variance of system response can be described by a complete mathematical model and the spectral density distribution in general form.

The higher frequencies of a system tend to be closer to each other; therefore has to be decided from case to case whether this has a large influence on the system response. For multi-degree of freedom systems with well-separated modal frequencies the estimation of the response variance can be simplified in such a way that the earthquake excitation can be substituted by spectral density of limited band width or with spectral densities of general form considering the discrete values of the functions and without coupling terms in mathematical model.

However it is to be considered in this case, i. e. for general stationary excitation (non-white noise) that the stationary part of the response may be approximated with the white noise response under the following conditions: The excitation power spectral density varies slowly with ω) in the neighbourhood of ω_o (the system natural frequency); and the major contribution of the spectral density to the response comes from the neighbourhood of ω_o . The effect of non-stationarity on the response of a light secondary system can depending upon the system properties of primary and secondary systems, the type of stochastic excitation or the initial conditions, etc. - sometimes be of importance. If these are not considered then unrealistic results can be obtained. This is to be considered particularly in connection with the long period and small damped systems subjected to relatively short duration of excitation. The effect of non-stationarity decreases very quickly at higher damping and when the systems are rigid and the duration of the excitation is sufficiently long.

3. Conclusions

For the application of stochastic methods on earthquake problems, individual decisions are necessary regarding the choice of the mathematical model in connection with the reliability of the results, character of the excitation and the properties of the systems. If the natural frequencies are not having closely spaced modes and the damping is small then the deterministic method lead, in the case of stationary and sufficiently long excitation, to some comparatively good results available by stochastic methods. In the other cases mentioned beforehand the stochastic procedures are preferred as they allow a realistic determination of the system response.

In no case the conclusion can be drawn that the deterministic methods lead to unusable results because they are conservative in most cases. The stochastic procedures deliver on the other hand additional statements on the probability distribution of structural response and on the estimation of the probability of exceeding a definite and unpermitted limiting value of the system response.

The comparison of the methods of analysis with respect to convenience of use, accuracy, ability to predict inelastic response and economy is briefly given in Table I.

References

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DETERMINISTIC APPROACHES

Assessment criterias

- Usefulness of the type of solution
  (time history, response spectra, etc)
- Type of analysis
  (coupled or decoupled)
- Type of connection between the primary and secondary system
  (number and positions of the connecting points)
- Type of combinations of individual effects
  (earthquake spatial effects, support excitations points, modal components and the order of combination -procedure sequence - used for all three effects)

Fig. 1 Assessment criterias for deterministic approaches

STOCHASTIC APPROACHES

Assessment criterias

- Influence of system properties
  - fundamental frequency
  - distribution of frequency
  - damping values
- Type of idealisation of exitation
  - white noise with limited bandwidth
  - approximation of the defined spectraldensity-function by white noise
  - analytically defined spectral density
- Influence of nonstationarity
  - initial conditions
  - duration of exitation
  - damping
  - systems behaviour

Fig. 2 Assessment criterias for random vibration approaches

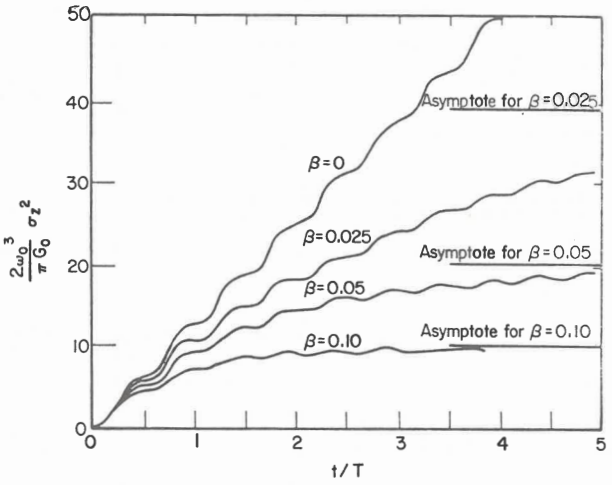

Fig. 3 Variance of SDF response to white noise base excitation G_0.

This Figure shows the response duration, in number of system periods required to attain stationarity for different levels of damping (β).

$$\alpha_{kl} = \frac{\int_{-\infty}^{+\infty} H_k(\omega) H_l^*(\omega)\, d\omega}{\int_{-\infty}^{+\infty} |H_k(\omega)|^2\, d\omega}$$

This ratio represents the significance of individual modal coupling terms between the vibration shaps k and 1.

H_k, H_1^* - the complex frequency response function and the complex conjugate for mode k or 1 respectively.

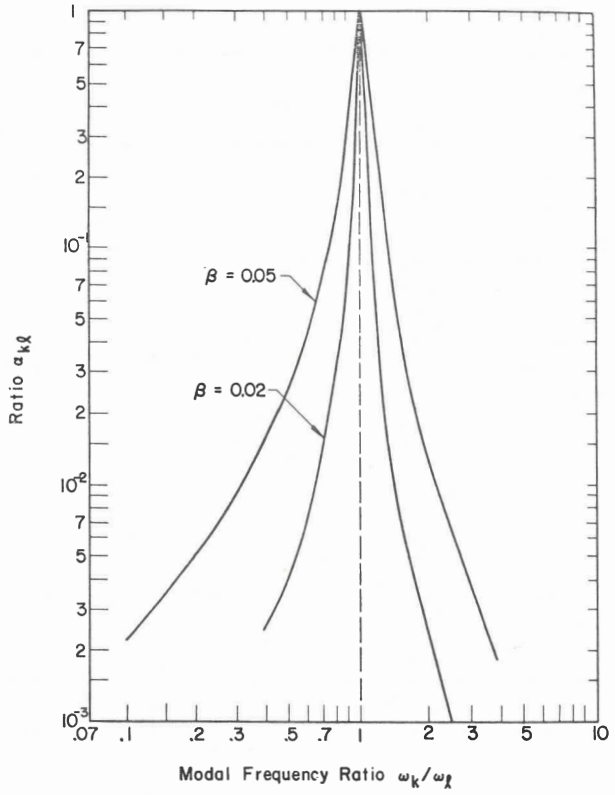

Fig. 4 Modal coupling VS modal frequency ratio.

Table I : EVALUATION OF RESPONSE OF MULTIDEGREE-OF-FREEDOM MECHANICAL STRUCTURES
COMPARISON OF THE METHODS OF ANALYSIS

Methods	Convenience	Accuracy	Cost of Analysis	Nonlinear Structures	Remarks
1. Response Spectra	Very Convenient	Response results are reasonably accurate. Inaccuracies in some special cases such as close frequencies have, however, been oberserved	Very Reasonable	Can be used to obtain design response, if inelastic response spectra are used. However, only approximate results is obtained	
2. Time History (Modal Analysis)	Convenient Requires generation of spectrum-consistent time history	Analytical results are accurate for a given time history. However, results for two independent time histories consistent with a given response spectra may be different	Costly	Has limited applicated	Commonly used in generating floor response spectra required in design of secondary systems
3. Time History (Direct Integration	Same as above	Require adaption of sufficiently small time step increment to avoid solution stability problem in response estimation for high frequencies.	Very Costly	For accurate response estimation of nonlinear structures it is one of the approches available presently	Require choice of nonmodal damping characteristics.
4. Random Vibration (PSDF)	Convenient to adopt. Design P.S.D.F. of characterizing the seismic load is required	Results are reasonable	Reasonable	Requires further research effort in this area	As an ensemble of time histories is represented by P.S.D.F., used in this method the response results of general validity are obtained.
5. Static Methods	Very convenient for some simple structures	For elastically designed structures with inadequate ductility provisions. The results may be unconservative.	Inexpensive	Very useful for simple elasto plastic structures.	Justification usually required by the regulatory agency to establish the validity of any simple static method.
6. Fourier Spectrum	Very convenient	Results can be very accurate provided sufficient number of steps are used.	Reasonable	Require further research effort in this area.	The folding frequency should be selected proper.