FORCED VIBRATION TESTS AT A NUCLEAR POWER PLANT

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SYNOPSIS

This paper presents the method and the results of forced vibration tests of the reactor building at a nuclear power plant. Authors propose the method to identify eigen-parameters which constitute transfer functions obtained from the tests and the method to reduce to the mathematical model which is able to represent dynamic characteristics of the system concerned. This method is applied to the experimental results of the building. In consequence, it is made clear that aseismic design of this reactor building is good enough.

INTRODUCTION

Tokai No.2 Nuclear Power Plant containing BWR-type reactor is one of the largest plant in Japan generating the electricity of 1100MWe, which was built in Tokai village by The Japan Atomic Power Company. As a matter of course, much attention is paid in the aseismic design of the important structure such as the reactor building.

The forced vibration tests of the reactor building at that plant were carried out in Feb.'77. The purpose of the tests was to grasp the dynamic characteristics, to inspect the validity of the aseismic design and to obtain useful data for aseismic design in the future. In the tests, 450 ton mechanical vibrator and data acquisition-analysis system were used which were developed by Central Research Institute of Electric Power Industry (CRIEPI). This paper summarizes the results of the tests and presents the considerations on the experimental results.

OUTLINE OF THE TESTS AND THE RESULTS

Description of the Reactor Building

The concrete mat of the reactor building is 70m square. The building is of reinforced concrete, 56m high above the ground and reaches to the depth of 17m under the ground. It weighs about 2.8×10^5 ton in total. That is, the building is a large-scale, weighty structure with high rigidity. As shown in Fig.1, the reactor building is settled on the mud rock through man-made rock. The ground structure around the plant is shown in Fig.2. The reactor building is adjacent to the turbine building. There is a space of 5cm between two buildings and expansion materials are inserted to the space underground. When the tests were carried out, the construction of two buildings was almost completed, however, the top parts of PCV,RPV were put temporarily on the floor of El.46.5m and there was no water in the fuel storage pool, in the suppression pool and in the reactor.

Method of The Tests

Block diagram of 450 ton mechanical vibrator system is shown in Fig.3. This system consists of three vibrator units, each of which has the vibrating force of 150 tonf, but only two units were used in these tests.

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Fig.4 shows the performance of the vibrator. In these tests, however, a constant force excitation pattern was adopted. In this pattern, the exciting force is kept constant above a certain frequency range as shown in Fig.5.

On every floor of the reactor building, at least one set of transducers (velocity type, T_0= 1 sec) was arranged, and moreover, some were added as the needs of the case demanded. The signal of each transducer is transmitted to data acquisition-analysis system and is processed at the optimum sensitivity under the control of the computer which monitors each signal. After FFT processing, signals in time domain are transformed to the transfer function as shown in Fig.6-Fig.9. As is obvious from the transfer functions shown in the figures, damping forces act in each element of the structure. So hereafter, main formulation below are based on complex modal analysis theory.

DATA REDUCTION AND THE RESULTS

Outline

From the transfer functions of every floor, eigen-values, eigen-vectors and generalized masses (hereafter, those parameters are called modal constants for short) are identified by non-linear multi-regression analysis. Then aseismicity of the structure concerned is examined through the computation of earthquake response to hypothetic earthquake in design. These modal constants are then transformed to system parameters which consist of mass, damping and stiffness matrices ($\mathbb{M}, \mathbb{C}, \mathbb{K}$). It is an object of this identification to obtain data for aseismic design in the future through estimating explicitly spring constants and damping coefficients and masses.

Fig.10 shows the procedures of the method proposed in this paper in comparison with those of usual numerical simulations.

Identification of Modal Constants and The Results

In the forced sinusoidal vibration, equations of motions are presented as

$$\mathbb{M}\ddot{\mathbb{X}} + \mathbb{C}\dot{\mathbb{X}} + \mathbb{K}\mathbb{X} = \mathbb{F} \exp(i\omega t) \qquad (1)$$

where $\mathbb{M}, \mathbb{C}, \mathbb{K}$ are system parameters, $\mathbb{X}$ and $\mathbb{F}$ are the displacement vector, and the force vector, respectively. Eq.(1) can be transformed to

$$\mathbb{X} = \sum_{r=1}^{R} \left\{ \frac{\mathbb{U}_r^T \mathbb{F} \mathbb{U}_r}{a_r (i\omega - \lambda_r)} + \frac{\mathbb{U}_r^{*T} \mathbb{F} \mathbb{U}_r^*}{a_r^* (i\omega - \lambda_r^*)} \right\} \qquad (2)$$

where $\mathbb{U}_r$, λ_r and $a_r = \mathbb{U}_r^T (2\lambda_r \mathbb{M} + \mathbb{C}) \mathbb{U}_r$ represent r-th eigen-vector, r-th eigen-value and r-th generalized mass, respectively. In Eq.(2), * means conjugate operation and T transposed.

Modal constants are identified according to the next procedures as shown graphically in Fig.11.

(1) On reference to transfer functions obtained from the tests, initial eigen-values λ_r(r=1,R) are assumed, where R means the number of modes.

(2) Eigen-vectors $\mathbb{U}_r$ (r=1,R) are identified which minimize the sum of squares of errors between $\mathbb{X}$ in Eq.(2) and observed transfer functions.

(3) Eigen-values λ_r(r=1,R) are again identified which minimize the same as that mentioned in the previous procedure (2).

(4) Procedures (2) and (3) are repeated until errors are less than allowable.

These procedures are almost the same as those by F.Calciati(Ref.1). In these procedures, successive approximation method is adopted, so generally, it takes too large amount of calculation to identify modal constants in case where many trasducers are arranged. In order to decrease the amount of calculation, the authors abbreviate the amount of calculation per an approximation step.

The coefficient matrix of the simultaneous equation which is formed to obtain approximational values of next step from given initial values is independent of each transfer function unless it is weighted. The coefficient matrix of the simultaneous equation is calculated, after each element of the coefficient matrix is resolved to its components and they are again put together on the base of their properties. As the result, as to time of calculation required per an approximation step, it only took almost the same time as to solve the 2R-dimensional simultaneous equation three times.

Identified modal constants are superimposed according to Eq.(2), and the results are also shown in Fig.6-Fig.9. Superimposed results are in very good agreement with observed transfer functions. Each order of eigen-values obtained from the identification of the modal constants is shown in Table 1, and the shapes of eigen-vectors from the 1st to 5th modes are shown in Fig.13.

In order to reduce the errors between them, it is sufficient to take more modes in Eq.(2). Really in these tests, when 13 modes were taken, superimposed results were almost complete accord with observed functions. In this paper, 8 modes are taken, the reason of which is mentioned below.

In case of earthquake response, equations of motions are presented as

$$\mathbb{M}\ddot{\mathbb{X}}+\mathbb{C}\dot{\mathbb{X}}+\mathbb{K}\mathbb{X}=-\alpha(t)\mathbb{M}\delta \qquad (3)$$

where δ and α are the directional vector of the earthquake and the ground acceleration, respectively. Now, let dynamic displacement be $X=p_1\mathbb{U}_1+p_2\mathbb{U}_2+\ldots$

Then, using orthogonal condition between modal vectors, Eq.(3) is transformed to

$$\dot{p}_r-\lambda_r p=-\alpha a_r^{-1}\mathbb{U}_r^T\mathbb{M}\delta \qquad (4)$$

Generally speaking, $\mathbb{M}$ can be assumed more accurately than $\mathbb{C}$ or $\mathbb{K}$. So, Eq.(4) is computable. But in this method, it results in neglecting the influence of the vibration of the unmeasured subsystem on the object system. Now let suffix o mean physical quantities of the measured subsystem, and suffix 1 mean those of the unmeasured subsystem. Then, right side of Eq.(4) results in $-\alpha a_r^{-1}(\mathbb{U}_0^T\mathbb{M}_0\delta_0+\mathbb{U}_1^T\mathbb{M}_1\delta_1)$, the second term of which is unable to be evaluated quantitatively. But represent the directional vector δ as the linear combination of $\mathbb{U}_r$ and compute participation factors. $\mathbb{U}_r$ has already been influenced by the unmeasured subsystem, so Eq.(4) can be calculated without using $\mathbb{M}$ directly. Earthquake response is thus possible using identified modal parameters. The results of computation to El-Centro NS'40 are shown in Fig.15 as compared with the design values. In this case, El-Centro wave was normalized to the maximum acceleration of 180 gal which was the same as that used in design.

In this stage, it is made clear that the critical damping ratio of the 1st mode of the reactor building is estimated as about 16%, which is far larger than the design value of 5%.

Identification of System Parameters and The Results

According to the method introduced here, system function has to be assumed in advance. Necessarily, system parameters are identified differently in reply to the type of the system function assumed in advance, for example, Lumped Mass Model, FEM or mathematically degenerated model of the dimension of R x R, where R is the number of modes taken. In this paper, Lumped Mass Model is adopted in conformity with the present aseismic design method.

Generally speaking, for each element of system parameters to be determined uniquely so as to have certain modal constants, behaviors of a great deal of places would have to be measured in the tests. As compared with the method to determine system parameters uniquely, the method is more realistic in which a certain function between elements is assumed basically and system parameters are identified through the variation of the function. In this paper, empirically obtained a-priori model is intended for basic function, and each element of this model is modified.

System parameters are identified according to the following procedures.

(1) Taking identified modal constants into consideration, a mathematical model is assumed empirically in advance. This mathematical model is hereafter referred to as a-priori model. (See Fig.12)

(2) Modal constants sensitivities are searched for when system parameters $\mathbf{M},\mathbf{C},\mathbf{K}$ change infinitesimally $\Delta M, \Delta C, \Delta K$.

(3) Quantities of the system parameters to be varied are evaluated and a modified model is identified so as to agree well with modal constants already identified from experimental results. In this method, not only the differences between both modal constants but also the differences between both transfer functions are taken into consideration as errors.

(4) Procedures (2) and (3) are repeated until errors are less than allowable.

These procedures are formulated with reference to the method by P.Ibanez(Ref.2), but differ from his method in the following regards. In the first place, this method is formulated based on complex modal analysis theory. Then, in this method, measurement errors are evaluated also in the domain of transfer functions. This is a method to modify quantitatively the dynamic characteristics of the mathematical model, and it has no function to create new relation, for example, to establish a new lumped mass, or a new spring between masses. So, the assumed a-priori model has to represent beforehand the behaviors basically superposed from identified modal constants. Otherwise, identified system parameters would get unrealistic. It is the reason why 8 modes are taken in this paper corresponding to the a-priori model shown in Fig.12.

Modal constants as the inputs for the identification of system parameters are shown in Fig.13 and Table 1 with "identified". After the procedures from (1) to (4) for identification of system parameters, a new lumped mass model is identified. Modal constants determined from newly identified model are also shown in Table 1 and Fig.13. The determined modal vectors are normalized so that determined generalized masses are equal to identified ones.

As is obvious from Fig.13, both vectors give good conformity with each other. But as to eigen-values in Table 1, determined critical damping ratios are fairly larger than identified ones. As mentioned above, system parameters are identified in this method so that transfer functions determined from newly identified model finally agree well with observed ones. Therefore, even if identified damping ratios are given, determined damping ratios are evaluated larger in such cases that determined transfer functions are larger than observed ones. This difference is considered to mean that it is difficult to represent identified modal eigen-values so far as the a-priori model is that shown in Fig.12. That is, in such a dynamic system as interaction between adjacent structures play an important role, grounds have to be incorporated in the model.

Identified new model cannot represent given modal eigenvalues accurately, but qualitative tendency and quantitative evaluation of observed transfer functions are represented well by the new model. It is because the element of the ground which is not included in the a-priori model is evaluated as damping forces.

Earthquake response of the identified Lumped Mass Model to El-Centro wave mentioned above was computed. Computed results are also shown in Fig.14. By the way, in earthquake response according to Eq.(4), shear force and bending moment cannot be obtained. Shear force and bending moment mentioned "identified" in Fig.14 are the results of computation in which acceleration response computed according to Eq.(4) occurs to the identified Lumped Mass Model. In Fig.14, there is some difference between both maximum accalerations, but almost no difference between both shear forces and both bending moments because each order of identified eigen-vectors and determined ones coincides well each other.

Comparing these values with design values, the response are about 1/2 -4/5 of the design value, and so, aseismic design of this reactor building is good enough.

CONCLUSION

(1) Forced vibration tests of the reactor buiding which is a large-scale weighty structure were carried out. In the tests, large powerful vibrators and data acquisition-analysis system are used. As the result, transfer functions of many measured points were obtained accurately.

(2) From the observed transfer functions, modal constants were identified which constituted the transfer functions. In the application of modal identification method to actual problems, a point of view was introduced what order of modes or how many orders of modes should be identified in relation to the mathematical model assumed.

(3) From identified modal constants, a numerical model with the physical background was identified. Eigen-vectors and transfer functions determined from the newly identified numerical model are in good accord with the identified eigen-vectors and observed transfer functions.

In the application of this method of identifying system parameters to actual problems, a point of view was introduced as to the situation of the a-priori model assumed beforehand in relation to the errors generated in the identification.

(4) These methods were applied to the results of the forced vibration tests of the reactor building. As the result, it was made clear that aseismic design of this building was good enough.

ACKNOWLEDGMENT

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(2) P.Ibanez "Identification of Dynamic Structural Models from Experimental Data" Ph.D. Thesis Univ. of California, LA 1972

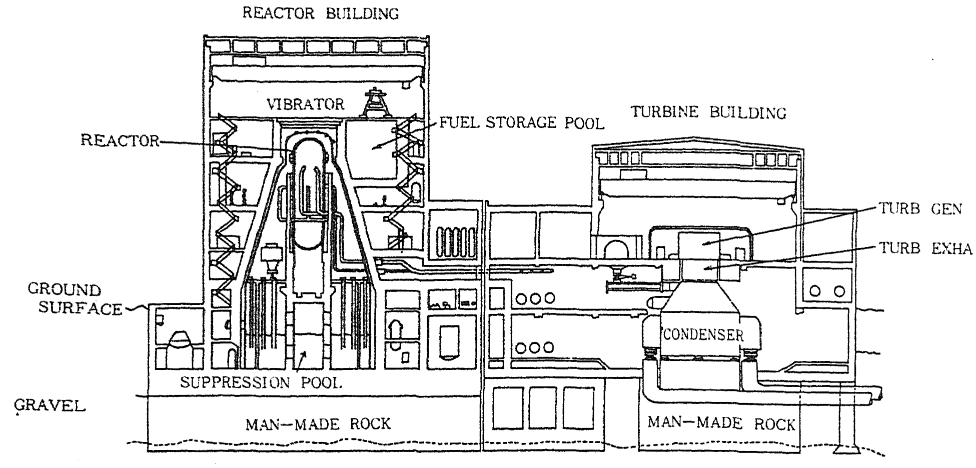

Fig. 1 THE FORCED VIBRATION TESTS IN OUTLINE (TOKAI NUCLEAR POWER PLANT NO. 2)

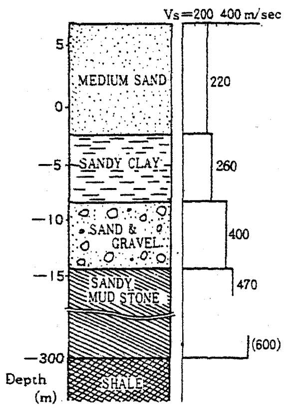

Fig. 2 Ground Structure

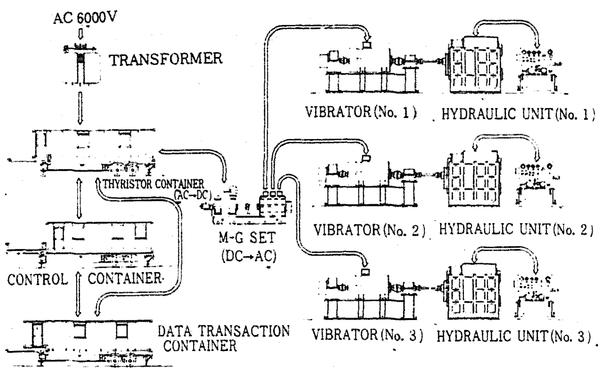

Fig. 3 Block Diagram of Vibration Exciter System

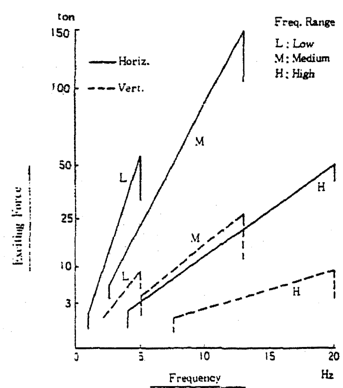

Fig. 4 Performance of Vibrator

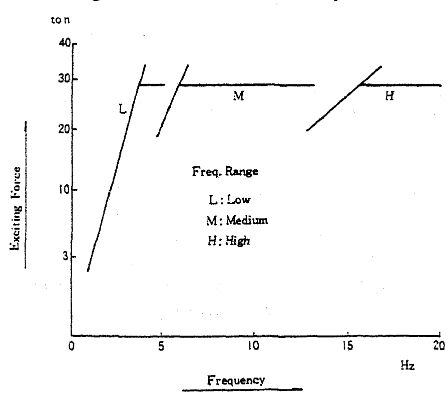

Fig. 5 Actual Exciting Force

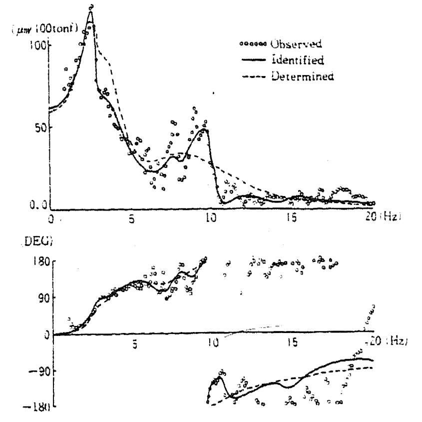

Fig. 6 Transfer Functions Observed, Identified and Determined (EL. 63. 65m)

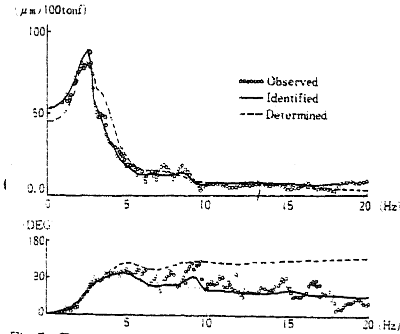

Fig. 7 Transfer Functions Observed, Identified and Determined (EL. 46. 5m)

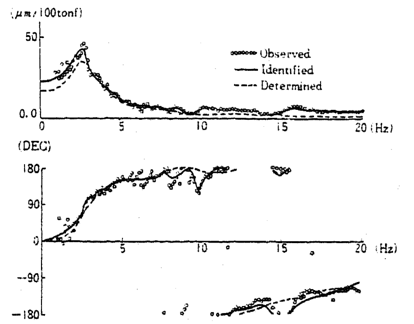

Fig. 8 Transfer Functions Observed, Identified and Determined (EL. 20. 3m)

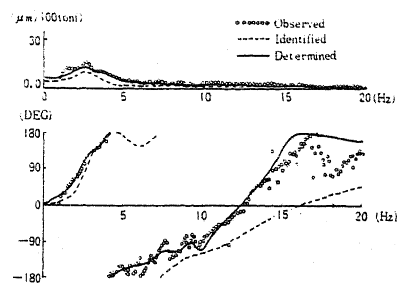

Fig. 9 Transfer Functions Observed, Identified and Determined (EL.—4. 0m)

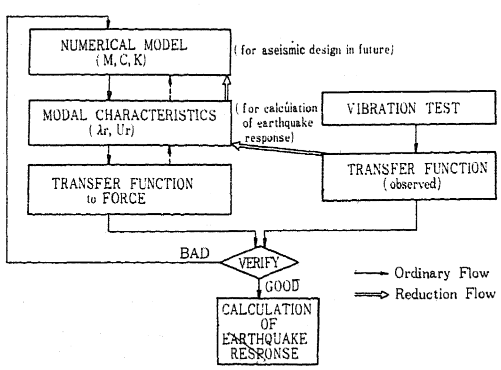

Fig. 10 Schematic Flow of Data Reduction in Comparison with Ordinary Simulation

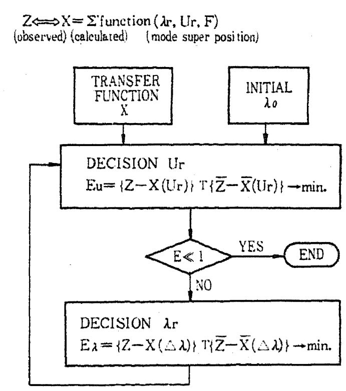

Fig. 11 Flow for Identification of Modal Const.

Table 1. Identified Eigen-Values and Determined Ones from Model

	IDENTIFIED					DETERMINED				
	1 ST	2 ND	3 RD	4 TH	5 TH	1 ST	2 ND	3 RD	4 TH	5 TH
f (Hz)	2.76	3.43	7.66	8.58	9.90	2.67	3.69	6.89	8.23	10.8
h	0.16	0.27	0.11	0.13	0.05	0.18	0.22	0.20	0.25	0.18

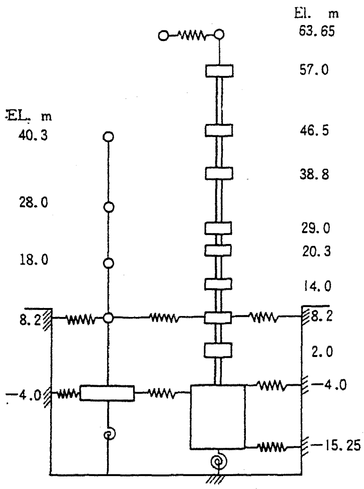

Fig. 12 Model of Structure System

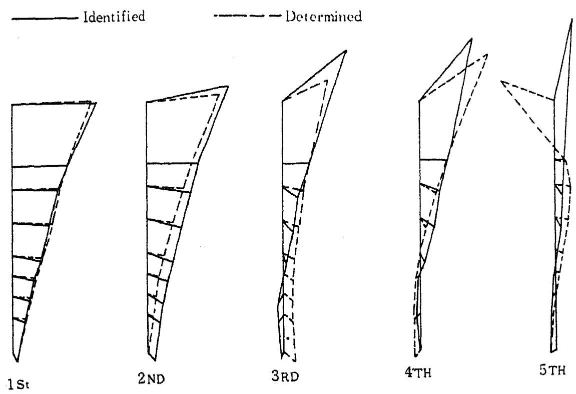

Fig. 13 Identified Eigen-Vectors and Determined Ones from Model

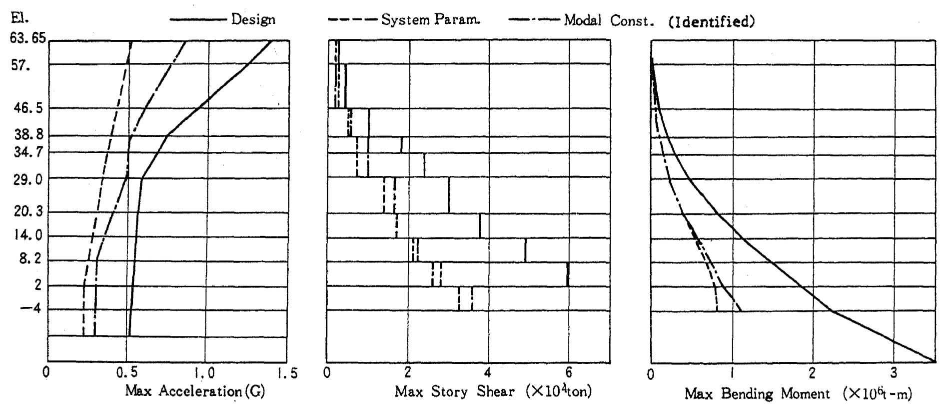

Fig. 14 Estimated Max Responses in Comparison with Response in Design