VIBRATIONAL CHARACTERISTICS OF PRIMARY REACTOR COOLANT SYSTEM

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It is exceedingly important from a standpoint of examining securities that to recognize what response may be shown when the primary, reactor coolant system, one of the main equipments of a nuclear power station, is suffered from an earthquake.

However, as the primary reactor coolant system (Abbreviated to RCS hereafter.) has complex structure consists of equipments and pipings having respectively very many variations in stiffness or mass distributions, it is necessary to examine throughly to find most proper way for modeling.

Though the vibrational test with actual machine is one of the methods for confirming vibrational characteristics of RCS, it is impossible to inflict large amplitude in actual machine test generally. It has to be defined that a relevancy of vibrational characteristics of RCS between the results of a large earthquake and of a little amplitude test.

Therefore herewith, in order to examine following problems we have carried out a vibrational test with 1/4-scale plastic model of RCS loop.

(1) Modeling methods for the purpose of to improve analytical accuracy for RCS loop.

(2) The support condition and vibrational characteristics for each equipment.

(3) Propriety of local excitation test on actual machine carried out as a link of the pre-service inspection.

1. Preface

The examinations of security for the nuclear power stations have become more siverely day by day. It is particularly important on Registant Earthquake Desing of nuclear reactor that the vibrational characteristics of RCS, one of main equipments in PWR plant, to be elucidated satisfactory.

The RCS of PWR reactor consists of a steam generator, a primary coolant pump, a pressure accelerator and the pipings which are connecting them (hot leg, cold leg and cross-over leg) taking the reactor vessel as the center.

These structual systems are a congregation of equipments and pipings having very many variations in stiffness of mass distribution, and also they are supported by complicated system with high stiffness.

With the intention of examining vibrational characteristics of thus complicated structure minutely, we carried out a vibrational characteristic test with 1/4-scale plastic model of RCS loop arranging.

The purpose of the experiments was as undermentioned.

(1) To ascertain the propriety of customary analytical method by means of examining the state of vibrational characteristics for steam generator and RCP which has different supporting structures.

(2) To examine the propriety of datas obtained by a local excitation such as in a excitation experiment carried out with actual machine as a link of pre-service inspection.

(3) To recognize the relevancy between vibrational amplitude and damping characteristics of the equipments and piping system.

2. Outline of Structure

The structure of RCS consists of steam generator, coolant pump and the pipings connecting them, namely, hot leg, cold leg and cross-over leg, taking a reactor vessel as the center.

Fig. 1 shows the structure.

Reactor Vessel is fixed to a inner concrete basis at the nozzle part of coolant gateway, and primary coolant pump as well as steam generator are supported by hinged holding legs so as to be movable horizontally for thermal extensions of piping system.

The oil snubber or the stopper are adapted in order to allow thermal extensional displacement as two steps of upper and lower sides horizontal supports, attached with primary coolant pump and steam generator for the purpose of aseismic support and of protection piping.

2.1 Support structure of actual machine

2.1.1 Structure of upper-side support of steam generator

The structure of steam generator upper-side support in this test is shown in Fig. 2.

2.1.2 Structure of lower-side support of steam generator

The structure of lower-side support of steam generator in this test is shown in Fig. 3.

2.1.3 Upper-side support of primary coolant pump

The structure of upper-side support of primary coolant pump in this test is as shown in Fig. 4.

2.1.4 Structure of lower-side support of primary coolant pump

The structure of lower-side support of primary coolant pump in this test is shown in Fig. 5.

It is connected with inner concrete by three tie-rod which has pin with both ends.

2.1.5 The legs of steam generator and primary coolant pump

The legs structure of steam generator or coolant pump is connected to inner concrete floor with four beams or three respectively by pin ends rod (only on inside way of surface).

As example of arranging situation of center lines of leg pins is shown as Fig. 6.

2.2 Calculation model

The primary coolant system is composed of reactor vessle, steam generator and coolant pump, taking the reactor vessel as the center. In this case, the reactor vessel is so solid that modelling is done with it taking as a fixed point.

Fig. 7 shows an example of mathematical model for designing calculation.

In designing calculation, each supporting structure is treated as follows.

(1) Center of reactor vessel: Fixed as shown in Fig. 8.

(2) Supporting structure: A method of carrying out analysis as whole structual system, with the supporting structure making into model directly owing to the shape and the stiffness of its equipments, or another method of substituting the supporting structure equipments for equivalent spring, with the stiffness calculating out by structual analysis previously.

(3) Oil snubber: A method of substituting stiffness for equivalent spring.

3. Manufacturing of Model and Experiment

Largeness of model is decided by conditions as of largeness and characteristics of the shaking table, easiness of experiment and manufacturing cost, etc.

As the result of examinations, it had been decided that 1/4-scale plastic model to be adopted.

3.1 Similarity law of model

In case of adopting 1/4-scale plastic model, the similarity law between prototype and model is able to be calculated by Buckingham's π-theorem.

Physical properties of the plastic materials applied to the model is as shown in Table-1, and similarity law of the model is given as Table-2.

As recognized as above, the frequency ratio of 1/4-scale plastic model is fp/fm = 0.95 and its frequency is nearly equal to that of prototype.

3.2 Construction of Model

It is as undermentioned that has been taken into consideration for modeling after prototype.

(1) Internal structure and water on the steam generator and rotary part of coolant pump of the model were modelized as a virtual mass so as not to contribute to stiffness of the model.

(2) The snubber of steam generator upper-side supporting structure has been constructed as equivalent to cantilever beam having equal stiffness to calculated value of equivalent stiffness and has been supported at one point.

(3) The upper-side support or coolant pump has four air snubber, which have been attached by hollow round bar such as not carrying any buckling, and tensile stiffness and the like has been made to equivalent.

(4) The horizontal supporting members and tie-rods of lower-side support for steam generator as well as for coolant pump are simulated by plastics members as the reducted-scale model.

(5) Besides, the stiffness of main steam pipe or main feed water pipe has been neglected at a stage of modelling, for it may be ignored beside the stiffness of other supporting structures or pipings.
Fig. 9 and Fig. 10 show respectively 1/4-scale plastic model and its calculation model thus manufactured.

3.3 Method of Experiments

The contents of experiments are as follows.

(1) Vibrational characteristics test
  - (a) Test for looking out the vibrational characteristics whole system by means of shaking table excitation.
  - (b) Test for looking out vibrational characteristics of the system with local (cross-over leg) excitation on the model, which is carried out as preservice inspection.

(2) Earthquake Response Test
Test for looking out response characteristics in case of an earthquake, by giving seismic wave excitation on a shaking table.
The method of experiment is shown in Fig. 11 and Fig. 12.
The specification of the shaking table used in the experiment is as Table-3.
Input wave adopted earthquake response test are followings.
  - (a) El-centro wave
  - (b) Golden Gate wave
  - (c) Random wave

4. Results of Experiment and its Consideration

4.1 Vibrational characteristics

We made a comparison of whole excitation test on a shaking table with local excitation test by means of exciter, as well as that of prototype (Local excitation test) surveyed value with analysis calculated value.

The results of above has been manifested together in Table-4.

It may be concluded as follows from these results.

(1) The experiment value, prototype test value and analysis calculating value are corresponded well each other.

(2) The prototype surveyed value are indicated lower a little as in Table-4 (Case-A).
This result depend on the effect of stiffness of the shim which was inserted to a gap at prototype survey at cold condition.

(3) By means of the model experiment, the relevance between input acceleration and vibrational characteristics have become clear as Fig. 13.

(4) Because each result of whole excitation test on the shaking table and local excitation test with exciter is coinciding well, the significance of pre-service inspection has been proved.

(5) Fig. 14 shows an example of the comparison on vibrational modes looked out minutely by model experiment with that of another gained by theoretical calculation. They are corresponding well each other.

As the result of seeking "The relevance between the vibrational amplitude and vibration damping ratio" by model experiment, it is understood that vibration damping ratio increases in proportion as increase of amplitude, as shown in Fig. 15.

4.2 Earthquake Response Characteristics

We have carried out earthquake response calculation by means of Modal Analysis Method.

First, we has searched out Response Spectrum of Model with seismic wave measured at several points on the shaking table and on the supporting structure making use of, then analyzed the response.

The follows are understood by the results of above.

(1) Fig. 16 shows an example of the comparison of the calculation value of seismic response with the results of model experiment.
As is known by the Figure, both of response at the top part of steam generator are considerable well accorded, but at the top part of the coolant pump experimented value shows a little larger in response than calculated value.

(2) This is caused by the lack of the stiffness of supporting structure of the test model.

(3) The upper-side supporting structure of the coolant pump plays a important part as the seismic-proof support.

(4) As for the seismic-response at the top of steam generator, though it shows larger response in cases of El-centro earthquake wave of which case the eigen value of steam generator accords to Dominant Frequency of response spectrum, in case of other seismic-wave the response is reduced by half.
Fig. 17 shows an example of experiment case and response magnification.

(5) Besides, as for the coolant pump, as the Dominant Frequency of seismic-response spectrum in Golden Gate Wave of this test accords to eigen value of the pump including the support structure, it shows high response magnification in case of this seismic wave.

(6) It is proved that, in spite of that the Response Magnification shows scattering in micro-view, it can be treated by Linear Analysis in macroscopical view as to the response near by designed seismic acceleration level.

5. Conclusion

There was difficult point of impossibility in elucidating it entirely, because of being hardly done any minute vibrational test sufficiently owing to various restrictions with the actual machine test at the site, but the characteristics of prototype have been made clear in detail this time, by means of carrying out "Vibrational Characteristics Test" and "Earthquake Response Test" with 1/4-scale model as follows.

(1) The vibrational characteristics of RCS Loop is able to obtain enough by means of linear model analysis as of today.

(2) The supporting structure for steam generator as well as primary coolant pump being adopted these day acted much effectively on earthquake proof, and seismic proof security has been confirmed by this experiments.

(3) The data obtained by local exciting test upon the prototype is reliable one, for it shows vibrational characteristics of system exactly enough.

(4) As the actual machine test is carried out under a cold circumstance at the site, it is necessary to estimate properly the stiffness value of the shim which is inserted into a clearance between the steam generator or the coolant pump and the supporting structures.

Table 1 Physical Properties of Plastic Material

Physical Quantity	Value
Specific Gravity	1.45
Youngs Modulus	2.7×10^4 kg/cm^2
Tensile Strength	590 kg/cm^2
Bending Strength	1000 kg/cm^2
Compressive Strength	830 kg/cm^2
Shearing Strength	630 kg/cm^2
Elongation	40 %
Charpy Impact Value	70 kg-cm/cm^2

Table 2 Similarity Law of 1/4-Scale Plastic Model

Physical Quantity	Simbol	Dimension	Similarity	Ratio of 1/4-Scale Model
Length	ℓ	L	$\ell_p/\ell_m = N$	4
Dength	ρ	ML^{-3}	ρ_p/ρ_m	5.41
Youngs Modulus	E	$ML^{-1}T^{-2}$	E_p/E_m	77.8 (67.8)
Strain	ϵ	—	$\epsilon_p/\epsilon_m = 1$	1
Stress	σ	$ML^{-1}T^{-2}$	$\sigma_p/\sigma_m = E_p/E_m$	77.8 (67.8)
Weight	W	MLT^{-2}	$W_p/W_m = \rho_p/\rho_m \cdot N^3$	3462
Spring Constant	K	MT^{-2}	$K_p/K_m = E_p/E_m \cdot N^3$	311.2 (271.2)
Force	P	MLT^{-2}	P_p/P_m	1.085×10^3
Displacement	x	L	$x_p/x_m = N$	4
Acceleration	$\ddot{x}$	LT^{-2}	$\ddot{x}_p/\ddot{x}_m$	3.60 (3.13)
Frequency	f	T^{-1}	f_p/f_m	0.948 (0.885)
Time	t	T	t_p/t_m	1.055 (1.13)

where, p: Prototype, m: Model, ( ): Hot Condition

Table 3 Specification of Shaking Table

Items	Quantity
Exciting Force	
(a) Case of Horizontal X-Y Direction	50 ton-g (each)
(b) Case of Horizontal One Direction	100 ton-g
Maximum Amplitude	±50 mm
Table Size	6m x 6m x 1m
Table Weight	21 ton
Maximum Loading Weight	100 ton
Frequency Range	0.1 ~ 50 Hz
Input Wave	Sine Wave Seismic Wave Random Wave
Shaking Method	Electri - Oil Pressured Servo Method

Table 4 Comparison between Calculated and Measured Frequencies of R.C.S.

Test Case	Natural Frequencies (Hz)				Remarks
	Measured			Calculated	
	Model Test		Actual Test		
	On Shaking Table	Local Excitation			
A	9.8	9.0	7.2	8.0	S.G-R.V. Direction
	8.8	8.1	5.2	7.6	Right Angle to S.G.-R.V.
	19.0	19.4	13.5	19.3	R.C.P.-R.V. Direction
	20.9	18.7	13.3	20.7	Right Angle to R.C.P.-R.V.
B (with gap)	2.7	2.7	4.4	3.3	S.G-R.V. Direction
	2.7	2.8	2.9	2.6	Right Angle to S.G.-R.V.
	8.2	8.0	9.1	9.2	R.C.P.-R.V. Direction
	7.2	7.1	8.2	8.2	Right Angle to R.C.P.-R.V.

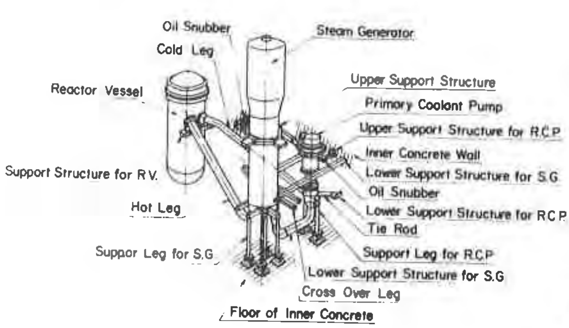

Fig 1 Outline of Structure of R.C.S.

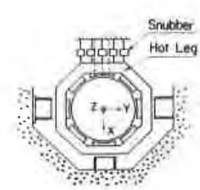

Fig.2 Upper Support of S.G.

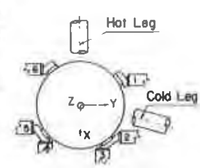

Fig.3 Lower Support of S.G.

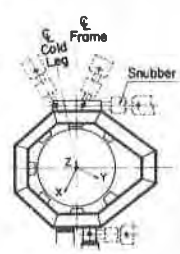

Fig.4 Upper Support of RCP

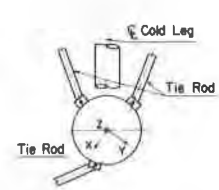

Fig.5 Lower Support of RCP

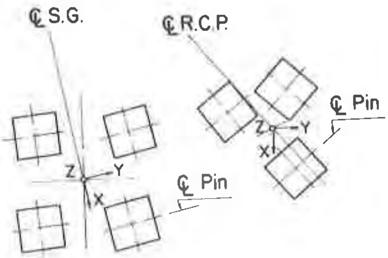

Fig.6 Arrangement of Support Leg of S.G. and R.C.P.

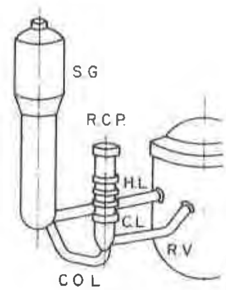

Fig.8 Piping boundary against R.V.

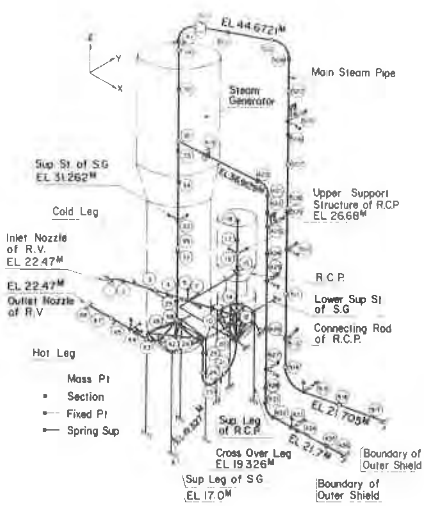

Fig.7 Mathematical Model for Vibration Analysis for Reactor Coolant System

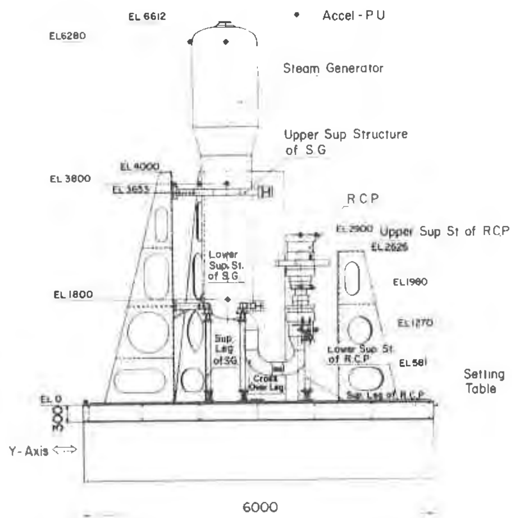

Fig 9 Measured Points on 1/4-Scale Model of R.C.S.

Fig. 10 1/4 Plastic Model

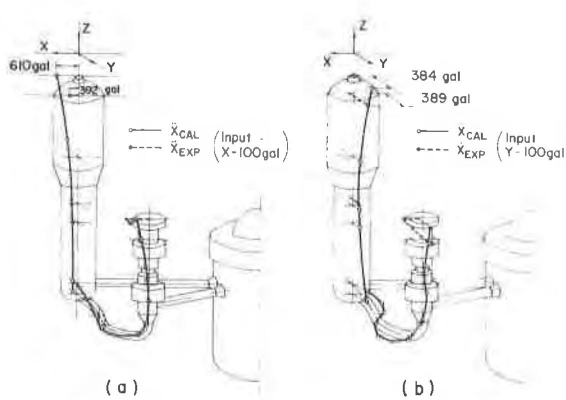

Fig.16 Earthquake Response (1 % Damping)

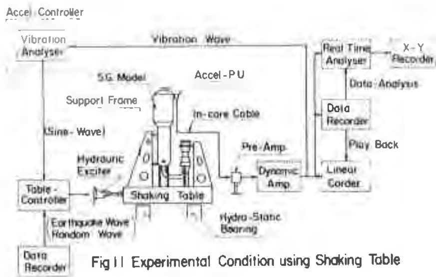

Fig 11 Experimental Condition using Shaking Table

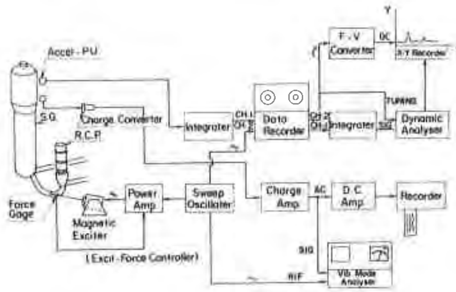

Fig 12 Experimental Condition by Local Excitation

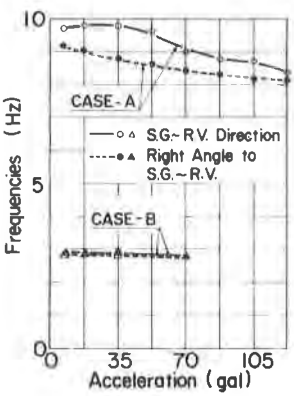

Fig.13 Relationship btw Frequencies and Acceleration

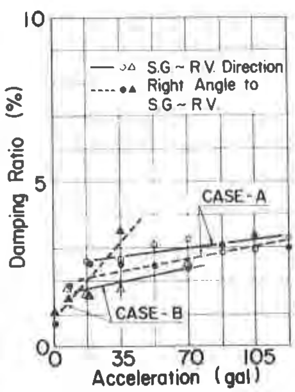

Fig.15 Relationship btw Damping Ratio and Acceleration

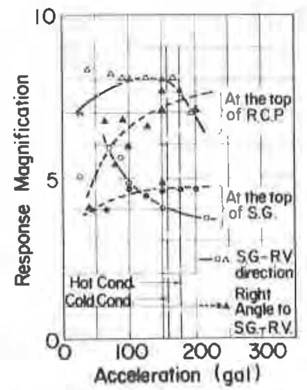

Fig.17 Relationship btw Response Magnification and Acceleration

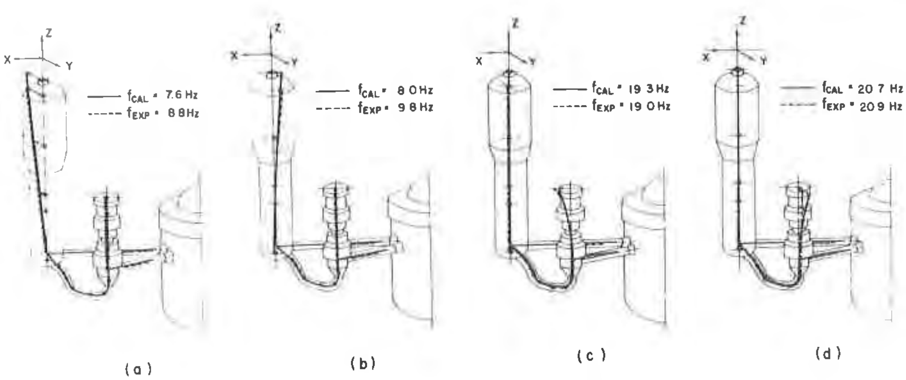

Fig.14 Natural Frequencies and their Modes