한국표준형 원자력발전소 제어봉집합체 보호구조물의 모우드 특성
(Ⅱ : 실험 및 실험후 해석)

Modal Characteristics of Control Element Assembly Shroud for Korean Standard Nuclear Power Plant
(Ⅱ : Test and Post-Test Analysis)

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ABSTRACT

The design of reactor internals requires the accurate vibration characteristics of each component for subsequent dynamic structural response analyses. For Korean standard nuclear power plant some modifications on the Control Element Assembly shroud from the reference design have been made. Since the shroud is complex in geometry having an array of vertical round tubes and webs in a square grid pattern, and being tied down by preloaded tie rods into position, it is planned to perform a vibration measurement program consisting of both experimental and analytical modal studies upon that component.

The shroud modal testing was performed on the low frequency global survey to measure the first several modes. The analysis using the finite element model was also performed for the as-tested conditions. The natural frequencies and mode shapes from both test and analysis have been acquired and compared to be in good agreement. It is concluded that finite element model generated is good enough to be used in the design for the dynamic response analysis under various loading conditions.

요 약

원자로내부구조물의 설계시 필요한 동적응답해석을 위하여 각 구조물의 정확한 진동특성을 파악할 필요가 있다. 한국표준형 원자력발전소를 위하여 설계된 제어봉집합체 보호구조물은 기존의 설계로 부터 많은 설계변경이 있었고, 또 이 구조물은 튜우브와 얇은 판이 사각격자형태로 이루어져 있고 연결봉에 의해 고정되는

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이논문에 대한 토론을 1993년 3월 31일까지 본학회에 보내주시면 1993년 9월호에 그 결과를 게재하겠습니다.

등 매우 복잡한 형태로 구성되어 있어서 해석과 시험에 위한 진동측정프로그램을 수행할 필요성이 대두되었다. 따라서 본 논문에서는 보호구조물의 진동시험을 수행하여 동적특성을 구하였고 또한 유한요소모델을 이용하여 해석에 의해 시험조건하에서의 고유진동수와 모두드형상을 구하였다. 시험과 해석에 의한 모우드특성을 비교한 결과 매우 잘 일치함으로써 구조물의 동적응답을 구하기 위한 해석모델의 타당성을 보였다.

1. INTRODUCTION

Reactor internals are the assembly of important structures located inside the reactor pressure vessel and supporting the reactor core from the various external loads, and they should be designed per ASME Boiler and Pressure Vessel Code Section Ⅲ subsection NG (Ref.1). A Control Element Assembly (CEA) shroud is one of the reactor internals structure that locates in the upper plenum of reactor vessel, and provides the passage of CEA insertion and withdrawal, and protects The CEA from the flow-induced loads. The CEA shroud consists of an array of vertical round tubes which are arranged in a square grid pattern. The tubes are joined by welding vertical plates called webs between adjacent tubes. the CEA shroud is mounted on twelve pads on the UGS base plate and is held in position by twelve tie rods which are threaded into the UGS base plate at their lower end. At their upper end, the pretensioned tie rods are held by nuts which bear on twelve plugs in the top of twelve of the CEA shroud tubes.

The reference design of CEA shroud has a very big force level considered from the pipe break excitation in the preliminary design stage and therefore there was a significant modification from the reference design (Ref.2) for Korean standard nuclear power plant (Ref. 3). Since the CEA shroud is complex in geometry as mentioned earlier and we need to have correct vibration characteristics to be used in the subsequent dynamic structural response analyses, it is plann to performed a vibration measurement program on the CEA shroud.

The modal test program consists of three phases; pre-test analysis, vibration testing, and post-test analysis (Fig.1). In the pre-test analysis, the natural frequencies and mode shapes of the CEA shroud are determined analytically using the three-dimensional finite element model. In addition, responses to the sinusoidal excitation applied at significant modal frequencies are calculated to provide guidance for the development of the test procedure in such areas as load application points, force levels required to excite the structure, and locations for response measurement (Ref. 4).

The vibration test itself determines the natural frequencies and mode shapes of the structure. The test results are then compared to the pre-test analysis. During the test, however, it was determined that the base structure was sufficiently flexible to affect frequencies and mode shapes of some lower modes. For this reason, a post-test analysis was done to incorporate the base plate flexibility in the CEA shroud analysis.

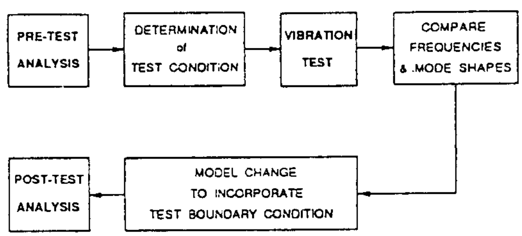

Fig.1 Schematic Diagram of Measurement Program

The vibration test results showed in general good agreement with the pre-test analysis except that somewhat lower values of natural frequencies were measured for the first several modes. After careful review of the test and analysis, it was concluded that these discrepancies were due to the different boundary condition for the tie-down plate structure. In the pre-test analysis, the base structure was treated as fixed rigid body. However, in the vibration test the motion of the base structure was detected and the rigid body assumption became no longer valid. Therefore, finite elements for the tie-down plate are added to the CEA shroud model in the post-test analysis.

By comparison of test and analysis results, the finite element model of CEA shroud developed may be verified to be valid for subsequent dynamic response analysis.

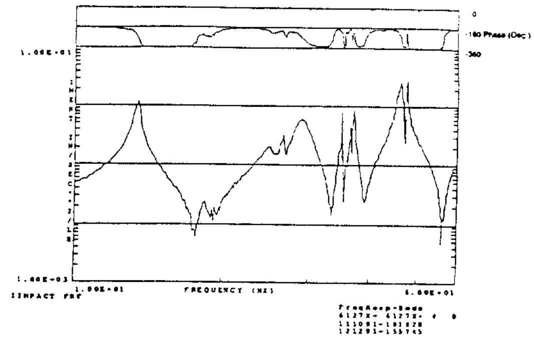

Fig.2 Driving Point FRF from Low Frequency Global Survey

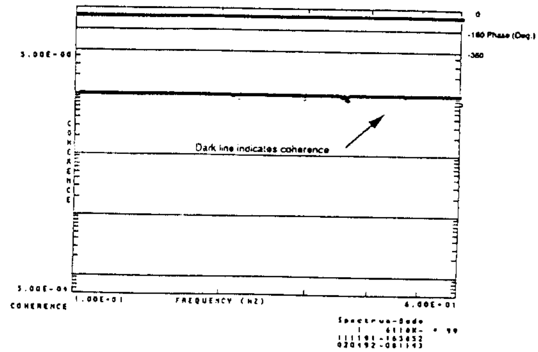

Fig.3 Coherence from Low Frequency Global Survey

2. VIBRATION TEST

A low frequency global survey of the shroud was performed to determine the frequencies of the first several modes. The pre-test analysis had shown these modes to be a horizontal rocking or bending mode, a second diameter mode and a third diameter mode(Ref.4).

2.1 EXCITATION

A three inch diameter hammer was used for excitation. The end of the hammer was equipped with a load cell for measuring the impact force and a rubber tip for controlling the frequency content of the imparted force. A representative driving point FRF is shown in Fig.2. The corresponding coherence function is shown in Fig.3. As can be seen by these functions, the quality of the data is very good. The FRF contains very little noise and the coherence is near unity across the entire frequency range.

An impact location for the low frequency global survey was selected by measuring driving point FRFs around half of the circumference of the shroud on the upper stiffening ring. The point numbers that were used on the stiffening ring were between 6101 and 6136. These points were marked on the upper ring in 10 degree increments from a reference location (Fig.4) which was one of the snubbers that had a zero degree marked scribed next to it. From the study of driving point FRF's around the ring, it was decided that two excitation locations would be used instead of one. The locations selected were points 6118 and 6123.

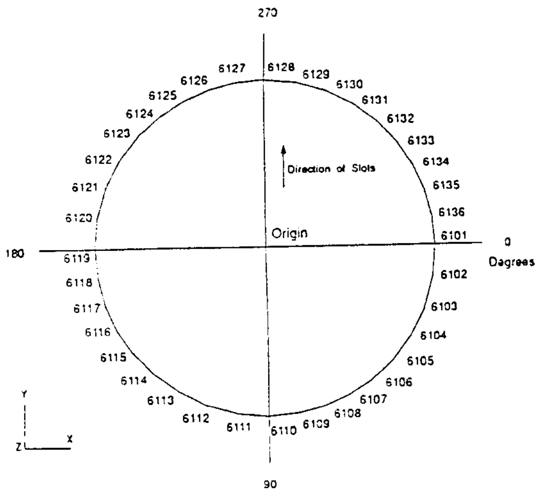

Fig.4 Undeformed Geometry for the Upper Stiffening Ring

While both locations indicate that the force was applied in the X-direction, the impact was actually radial. It was determined that not all the modes could be excited well from only one location.

2.2 TEST SET-UP

The shroud was set up in the fabrication area. It was mounted to a large T-slot table, anchored to the concrete floor using steel plates and threaded rod. All measurement and analysis equipment except the hammer and accelerometers were located remotely from the shroud. Fig.5 shows a diagram of the equipment setup used for this test. The test configuration basically consisted of the following equipment:

1. Transducers
   - -impact hammer for excitation
   - -accelerometers for measuring shroud response
2. Signal conditioning
   - -filters and preamplifiers and amplifiers
3. Analyzer

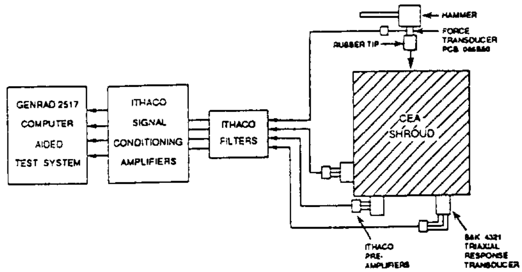

Fig.5 Schematic Diagram of Measurement System

   - -FFT analyzer for calculating FRFs and determining mode shapes.

2.3 DATA COLLECTION AND REDUCTION

All surveys that were performed used impact for the excitation technique. The analyzer data acquisition conditions used the maximum frequency of 64 Hz and exponential window. For impact excitation, a standard force window is applied to the force channel. This window decreases from unity to zero with a cosine shape over the 41st through 120th time point. Data before the 41st point is unaffected and all data beyond the 120th point is zeroed. In addition to this force window, it is possible to apply an exponential decay window to the tata. The purpose of this window is to ensure that the measured response of the structure decays to zero before the end of the block of data. The selected value determines the decay intensity of the window.

The low frequency global survey determined the frequencies and modes shapes associated with the first several modes of the structure. Measurement locations were selected so that the display could be generated that would be useful in studying the anticipated mode shapes.

The grid work of response measurement

locations had already been determined in Ref. 4. These locations were selected based on the nodes used in the analytical model. Where possible, the node numbering scheme that was used in the model was maintained for the testing. This should facilitate comparison between test and analysis.

For the initial survey, the following points were included:

1. Thirty-six locations in 10 degree increments around the circumference of the shroud along the upper stiffening ring.
2. Four longitudinal lines of 12 points along the length of the shroud were taken at 90 degree increments around the circumference.
3. A subset of 20 of the individual tube and web intersection points was used. They are shown in the geometry as straight lines across the shroud.
4. Twenty additional measurement locations were also included on the support structure and the concrete floor. This was done to determine what influence the support structure may have on the modes of the shroud.
5. Measurements were also taken at the top of the twelve tie rods. While measurements were only taken at single locations for each tie rod, the geometry was altered to indicate 4 at each rod to improve visualization.

The origin of the geometry for this coordinate system is shown graphically in Fig.4. The origin is similar to the origin used for the analytical model.

It should be noted that there is a difference in the number of locations that were measured in the 6118X survey and the 6123X survey. To collect as much useful information as possible, it was decided that the tube and web points would be collected for the 6118X excitation location only.

While measuring the shroud mode shapes, it was noticed that the T-slot table was weaker in the plane of the slots(bending about the X-axis). For this reason, the direction of the slots has been indicated in Fig.4. In addition, the location of the 0, 90, 180, and 270 degree scribe marks that were used as reference locations have also been shown in Fig.4.

For the low frequency global survey, two surveys were actually taken at the same time. Five impacts are used to excite the structure and the resulting acceleration measured at a group of points using a set of tri-axial accelerometers. Then, the set of accelerometers is moved from one group of locations to another, until the response has been measured and FRFs have been calculated at all locations. These collected functions can then be analyzed to determine mode shapes.

As the data was being collected during the shroud testing, mode shapes were generated. For the relatively low modal density and low damping of the shroud, the Total Response technique worked satisfactorily. However, several of the more closely spaced modes were curve-fit again. For the low frequency global survey, a SDOF fit was used to assure that the 3 modes in the 23 Hz to 29 Hz range were sufficiently separated. The Direct Parameter estimation method was used to define the modes located in the 45 Hz to 47 Hz range.

3. POST-TEST ANALYSIS

Very early in the vibration test, it was recognized that the support plate structure was introducing additional flexibility into the CEA shroud and that the post-test analysis phase should be implemented to account for this flexibility. The base setting for the test consists of a floor platen, 9 small plates and 10 overhanging tie down bars. In modelling the support plate structure, a fine mesh is used in the region of the small plates so that the interaction between platen and small plates can be varied to simulate different degrees of contact between two plates. The mesh of the small plate coincides with the platen mesh in the area of the bolts. The bottom tie rod node of the CEA shroud model as well as the bottom tie rod tube nodes also coincides with nodes on the small plate mesh.

The end nodes of tie down bars which are preloaded by very stiff beam clamped to the floor are fixed in all degrees of freedom to represent test conditions. Also the symmetric boundary conditions for the half symmetric model are included.

The assembly model contains 4306 plate elements, 66 pipe elements, 3 mass elements, and 3570 nodes. The model is built in 11 layers of elements connecting 12 levels of nodes. The base setting has 1020 plate elements, 18 beam element and 1064 nodes.

Using the finite element model mentioned above, modal analyses were performed. The reduced Householder procedure was used in the ANSYS code for eigenvalue extraction (Ref.5). The finite element model of the CEA shroud and the base support structure is shown in Fig.6. A summary of the results of the post-test analysis is provied in Table 1.

Table 1. Summary of Analytical Natural Frequencies

COMPONENT	MODE NO.	FREQ. (Hz)	REMARKS
Assembly	1	19.26	Fundamental rocking mode
	2	29.07	2nd diameter mode
	3	44.44	3rd diameter mode
	4	69.46	4th diameter mode
Tie Rod	1	35.02~37.93	1st beam mode

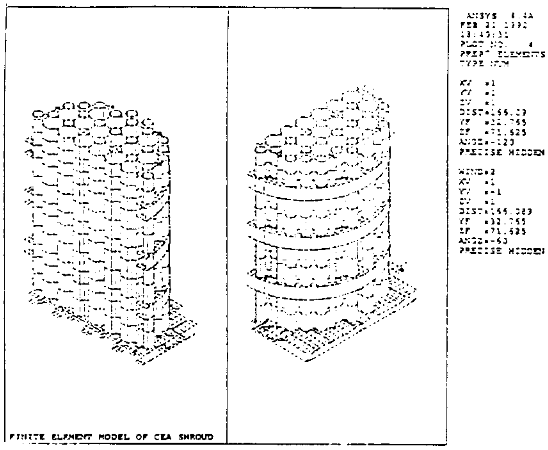

Fig.6 Finite Element Model of CEA Shroud

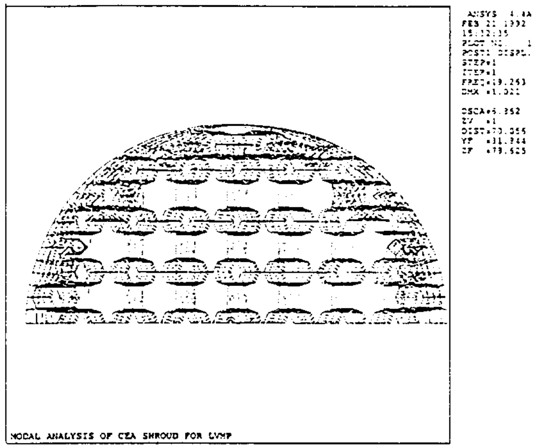

Fig.7 First Locking Mode from Analysis

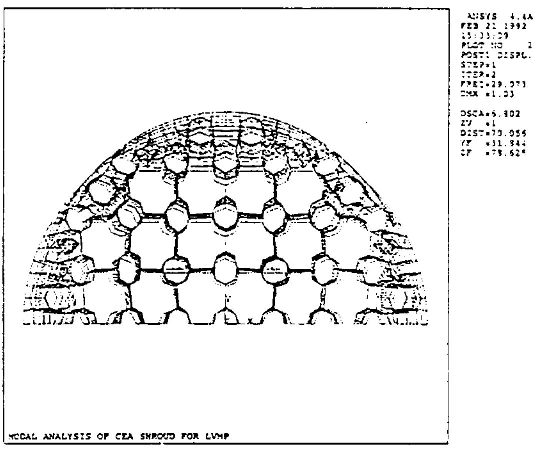

Fig.8 2nd Diameter Mode from Analysis

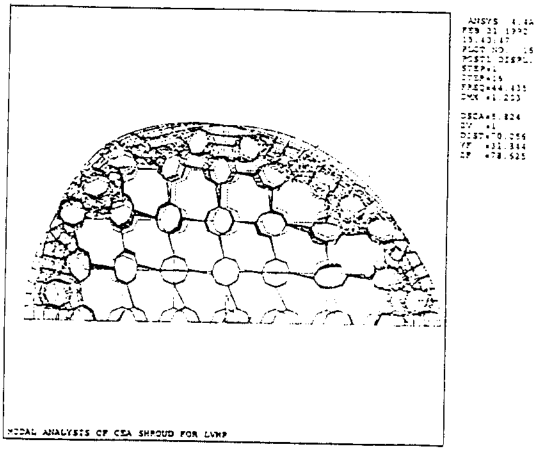

Fig.9 3rd Diameter Mode from Analysis

Mode shapes for the first three fundamental assembly modes, including the effects of the base structure used in the shop test, are given in Figures 7 through 9. Each mode shows the plan view of the shroud.

4. RESULTS AND DISCUSSION

A total of nine mode shapes was calculated for the test of low frequency global survey. Representative FRFs from the two low frequency surveys are shown in Fig.10. Table 2 provided verbal descriptions of the various mode shapes. A brief discussion of these modes is given below:

The first two modes at 13.5Hz and 18.5Hz were rocking modes of the shroud. The majority of the flexibility in these modes appears to be in the support structure. This is evident when studying the mode shape deformation plots. The table flexibility has the effect of significantly lowering the frequencies of these modes. For these modes to compare well with analytical predictions, the support stiffness in the model would need to be modified. Fig.11 shows the deformed mode shapes.

Table 2. Summary of Experimental Natural Frequencies

COMPONENT	MODE NO.	FREQ. (Hz)	REMARKS
Assembly	1	13.5	Y-direction rocking mode
		18.3	X-direction rocking mode
	2	25.3	2nd diameter mode of the shroud combined with vertical bending of the support table
		26.6	2nd diameter mode of the shroud with reduced bending of support table
		29.0	2nd diameter mode of the shroud: symmetric mode with 26.6 Hz mode
	3	45.3 46.1 47.3 47.7	These 4 modes all appear to be 3rd diametermodes with variations based on symmetry and support structure dynamics.
Tie Rod	1	33~38	1st beam mode

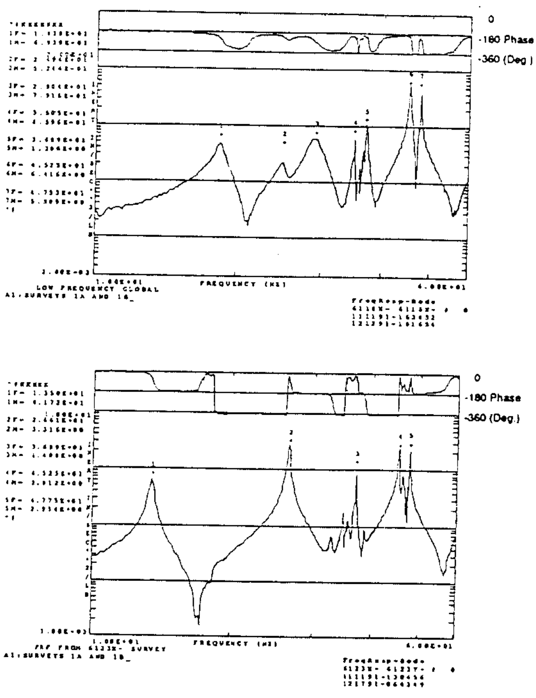

Fig.10 Driving Point(6118X : upper) and Cross(6123 : lower) FRFs from Lower Frequency Global Survey

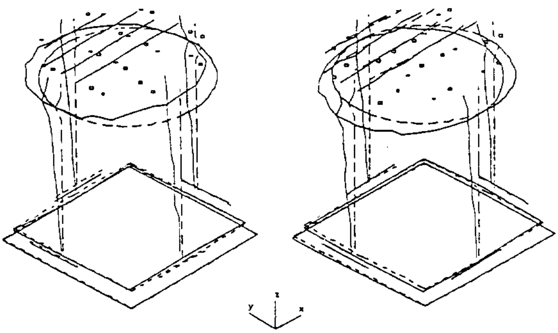

Fig.11 Y-and X-Direction Rocking Modes

Three modes were found that had the general shape of 2nd diameter modes when viewed from the top(Fig.12). The modes at 26.6Hz and 29.0Hz are a symmetric pair of 2nd diameter modes that are horizontally rotated approximately 45 degree from each other. The mode at 25.3Hz is a combined 2nd diameter mode of the shroud and support table vertical bending mode. Similar to the rocking modes described above, the flexibility in this mode is controlled in large part by the support structure. In this case, however, the table is bending vertically while the shroud is bending in a 2nd diameter shape. The table is bending about the Y-axis. This weak axis is defined by the direction in which the T-slots run along the table.

A set of four 3rd diameter modes was found in the 45.3-47.7Hz range(Fig.13). The variations in these modes are due to non-symmetry and support structure dynamics.

In addition to the modes listed in Table 2, there is a group of modes that shows up between 33 Hz and 38 Hz. These mode shapes look very similar to the global 2nd and 3rd diameter modes of the shroud. Based on the analytical model results, it was suspected that these peak may be fundamental tie rod modes. To confirm this hypothesis, single axis accelerometers were installed at approximately mid-span on each the tie rods one at a time. FRFs were then calculated for excitation at the 6118X impact location. These FRFs were compared to the shroud perimeter FRFs on the upper ring nearest each tie rod. These functions show a much greater response of the tie rod at these frequencies than on the adjacent location on structure. This is a very good indication that these peaks represent local modes of the tie rods rather than global modes of the shroud. The reason there are so many peaks in this range is that there are 12 tie rods. The analysis predicted 12 tie rod modes in the 33 to 37 Hz range.

By choice, to reduce the analysis model size and computer runing time, a half-symmetry model was used in both the pre-test and post-test analyses. The use of a half-symmetry model needs to be taken into account in the

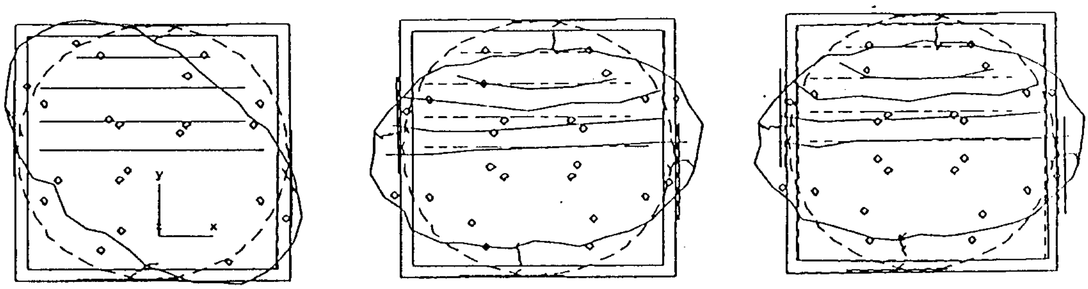

Fig.12 2nd Diameter Modes

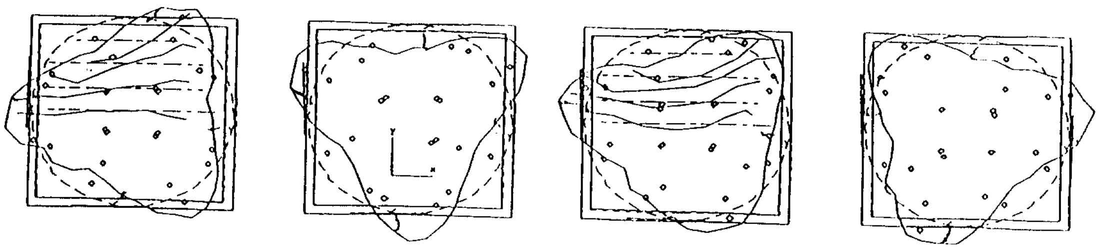

Fig.13 3rd Diameter Modes

proper selection of which test modes are directly comparable to the analysis modes. Additionally, in modeling of the base plate support structure, vertical master degrees of freedom were not used. This also needs to be taken into account in the selection of modes to compare.

In examining the vibration test mode shapes, the following points are noted. Fig.11 corresponds to the first assembly mode(cos θ mode). The modes associated with Fig.11 are symmetric about the Y-axis and the X-axis. The half-symmetry analysis model's corresponding cos θ mode shape (Fig.7) is symmetric about the X-axis. The second of Fig.11 mode shapes and its natural frequency are comparable, therefore, to those of Fig.7. This comparison results in a 5.5% differnece in frequency and excellent agreement of mode shapes.

Fig.12 corresponds to the second assembly mode(cos 2θ mode). The first of Fig.12 modes is symmetric about axes diagonal to the X-and Y-axis. The second of Fig.12 modes is symmetric about the X-and Y-axis, with small vertical support plate motion relative to horizontal shroud motion. The third of Fig.12 modes is symmetric about the X-and Y-axis, but with large vertical support plate motion relative to horizontal shroud motion. The half-symmetry analysis model's corrsponding mode shape(Fig. 8) is symmetric about the X-and Y-axis, with small vertical support plate motion. The finite element model of the base plate support structure has no vertical master degrees of freedom. The second of Fig.12 mode shapes and its natural frequency are comparable, therefore, to those of Fig.8. This comparison results in a 0.3% difference in frequency and excellent agreement for mode shapes.

Fig.13 corresponds to the third assembly mode(cos 3θ mode). The first of Fig.13 modes is symmetric about the X-axis. The second of Fig.13 modes is symmetric about the Y-axis. The third and fourth of Fig.13 mode are symmetric about an axis diagonal to the main axes. The half-symmetry model's corresponding mode shape(Fig.9) is symmetric about the X-axis. The first of Fig.13 mode shapes and its corresponding frequency are comparable, therefore, to those of Fig.9. This comparison results in a 2% difference in frequency and excellent agreement for mode shapes.

5. CONCLUSIONS

This paper determined experimentally the modal characteristics of the CEA shroud for Korean standard nuclear power plant. The analysis using the finite element model was also performed for the as-tested conditions. The natural frequencies and mode shapes from both test and analysis were compared to be in good agreement. It is concluded that finite element model generated was valid to be proper for the ensuing dynamic response analysis under various loading conditions.

REFERENCES

1. ASME Boiler and Pressure Vessel Code, Sec. Ⅲ, Rules for Construction of Nuclear Power Components, Division 1, Subsection NG, Core Support Structures, 1989.
2. M.J. Jhung, et al., "Optimal Design of Control Element Assembly Shroud," ANSYS Fifth International Conference, Vol.3, Pittsburgh, May 1991.
3. *K-SSAR:Korean Standard Nuclear Power Plant Safety Analysis Report*, Korea Electric Power Corporation, 1991.
4. M. J. Jhung, et al., "Modal Characteristics of Control Element Assembly Shroud for Korean Standard Nuclear Power Plant(I : Pre-Test Analysis)," J. of COSEIK, Vol.5, No.3, 1992.
5. G. J. DeSalvo and R. W. Gorman, *ANSYS User's Manual*, Swanson Analysis Systems, Inc., May 1, 1989.

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