제어봉집합체 보호구조물의 랜덤진동해석

Random Vibration Analysis of Control Element Assembly Shroud

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요 약

원자로 내부구조물을 구성하고 있는 중요한 구조물 중의 하나인 제어봉집합체 보호구조물에 대한 랜덤진동의 응답을 구하였다. 제어봉집합체 보호구조물은 본래의 설계로부터 많은 설계변동이 있었고 이에 대하여 많은 우려가 제기되었던 바 본 논문에서는 정상상태에서의 랜덤하중에 대한 동적해석을 수행하여 그 응답을 구하였고 이들을 실험치와 비교, 검토하였으며 제어봉집합체 보호구조물이 구조적으로 안전함을 보였다.

Abstract

The Control Element Assembly(CEA) shroud is one of the most important components in the reactor vessel internals for the nuclear power plant. Because of the severe modification from its original design the structural integrity of this component has been questioned. In an attempt to resolve this question, the response of the CEA shroud to a random loading in the actual operating condition is calculated analytically and experimentally and compared to the code allowables to show that it is structurally adequate and acceptable for the long term operation.

1. Introduction

Reactor vessel internals are the assembly of important structures located in the reactor pressure vessel and supporting the reactor core from the various external loads. A CEA shroud, one component of the reactor vessel internals that is located in the upper plenum of the reactor vessel, 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

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이 논문에 대한 토론을 1996년 9월 31일까지 본 학회에 보내주시면 1997년 3월호에 그 결과를 게재하겠습니다.

pads on the upper guide structure(UGS) support plate and is held in position by twelve tie rods which are threaded into the UGS support plate at their lower ends. At their upper ends, the pre-tensioned tie rods are held by nuts which bear on twelve plugs in the top of twelve CEA shroud tubes.

The original design of the CEA shroud had the first natural frequency which was coincident with the peak frequency of the response spectrum curve for the faulted condition and showed a significant flapping mode, generating high stresses which exceeded allowable limits. The flapping mode disappeared after attaching several stiffening rings around the shroud. The loaction of stiffening rings and the thicknesses of the tubes and webs were modified using the optimization routine and the optimized design showed that the modified CEA shroud is adequate for its design service[1].

Since it was required to have correct vibration characteristics of the CEA shroud to be used in the subsequent dynamic structural response analyses under the various loading conditions because of its complexity in geometry, it was planned to perform a vibration measurement program consisting of both experimental and analytical modal analyses upon that component on the shop. To determine the proper test conditions such as the number of measurement points, their locations, measurement frequency range and the excitation force level, the pre-test analysis was performed. The effects of the number of master degrees of freedom, holes in the tube and web and tie-rod preload on the natural frequencies were examined. The shroud modal testing was performed to measure the first several modes. The post-test analysis using the finite element model for the as-tested conditions was also performed. The natural frequencies and mode shapes were compared with test and these were found to be in good agreement. It was concluded that the finite element model generated was valid for the ensuing dynamic response analysis under the various loading conditions.[2]

In this paper the response of the CEA shroud for the random loading in the actual operating conditions is calculated as the final stage of the design. The CEA shroud is installed on the Yonggwang nuclear power plant unit 4 and during pre-core hot functional testing, flow induced hydraulic loads and vibration response are acquired. Root mean square(RMS) values related to structural response were computed and compared to acceptance criteria. The response stress levels were found to be quite low and well below the acceptance values and the code allowables. Based on this evaluation, it is concluded that the vibration response of the CEA shroud to random turbulence under normal operation is acceptable for long term operation.

2. Prediction

2.1 Model Development

A 30dimensional finite element model of the CEA shroud is developed from the model utilized in Reference 2 using the ANSYS code.[3] Most of the model is made up of elastic shell element SHELL63. This element may be quadrilateral or triangular. The remaining elements are elastic straight pipe element PIPE16 for the tie rod and 3-dimensional isoparametric solid element SOLID45 for the snubbers.

To model the ring behavior for comparison with the test, shell elements are used to explicitly represent the web and flanges of the channel. A single element is used through the web depth. The nodes lying on the ring web is made to lie exactly on the circle of mean web radius. The ring mesh for the test simulation requires that the outer tubes which are attached to the stiffener rings be modeled with octagonal cross sections for compatibility with the ring detail. The interior tubes are modeled similarly to enable direct comparison of modal characteristics between analysis and test. Using octagonal tube modeling requires additional levels of nodes to maintain the proper tube and web element aspect ratios.

The tie rod base nodes are fixed in all degrees of freedom to represent the preloaded clamped test conditions. Also the symmetric boundary conditions for the half symmetric model are included and the snubber is permitted to move in the radial direction only.

The entire model contains 4023 shell elements, 66 pipe elements, 8 mass elements, and 3605 nodes. The model is built in 11 layers of elements connecting 12 levels of nodes(Fig. 1). Nodes and elements numbering follows the sequential pattern of the bottom level.

2.2 Structural Response

A modal analysis of the CEA shroud is carried out to calculate the natural frequencies and modeshapes. The reduced method is used for the mode extraction where the HBI algorithm(Householder-Bisection-Inverse iteration) is applied for the calculation of the eigenvalues and eigenvectors. Fluid effects are accounted for by adding hydrodynamic mass, representing both contained and displaced water, to the structural mass.

The ANSYS code[3] is used to perform response analysis for random application, which is newly implemented at Revision 5.0. Response to random forcing functions consists of structural response of the entire CEA shroud assembly as well as of the individual tubes and webs. Assembly response is obtained using the model shown in Fig. 1. Base accelerations are applied to the model in the form of the Power Spectral Density(PSD) loading to determine the displacements and stresses in the tubes and webs from motion of the support plate (Fig. 2).

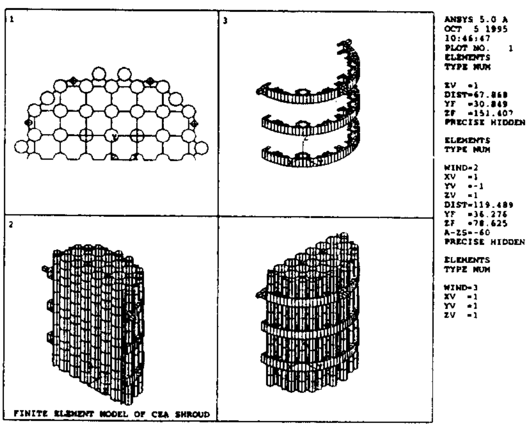

Fig. 1. Finite element model of CEA shroud

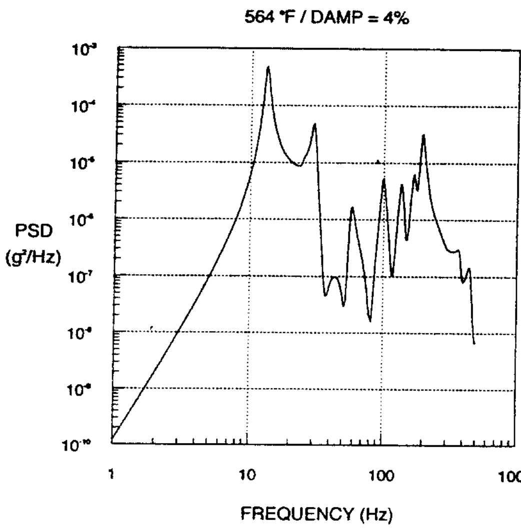

Fig. 2. Power spectral density at base support plate

In a separate analysis, a unit pressure is imposed on the tube, web and ring elements of the model to calculate the displacements and stresses in the tubes and webs due to direct loading from random turbulence in the coolant. Unit pressure loads of 1 psi are applied to the models to displace them into cos2θ, 3θ and 4θ modeshapes corresponding to the principal response modes. The resulting unit pressure modal stresses are factored by the response to unit pressure ratios to determine the response stress from each mode. These responses are then combined using SRSS methods to produce a total RMS stress. Strains are computed as the RMS stress divided by Young's modulus. The response pressure at each mode P_{RMS} is determined from the input PSD and the response equation.[4)]

$$P_{RMS} = \sqrt{\frac{\pi}{2} \cdot S_p \cdot f_n \cdot Q \cdot SF} \qquad (1)$$

where S_p=input PSD(psi^2/Hz),
f_n=modal frequency(Hz),
Q=1(2ζ)=amplification factor,
ζ=damping,
SF=shape factor.

The shape factor SF is found using the joint acceptance method and values described in Reference 4. A joint acceptance is determined for the hoop and axial directions using the wavelengths determined from the coherence of the forcing function, and the structural wavelengths from the modeshapes. The total joint acceptance is the product of the hoop and axial values. The results of these analyses are combined to provide detailed assembly response predictions at the instrumentation locations.

Significant resulting frequencies and modeshapes are shown in Table 1 and Fig. 3 and 4, respectively. Although 30 modal frequencies of the assembly are determined, modes 2 and 4 in Fig. 3 produce the majority of the response. Utilizing the structural natural frequencies and modeshapes obtained from

Table 1. CEA shroud assembly frequencies

(unit=Hz)

Mode	Shape	Temperature(°F)					
		150	200	260	360	500	564
1	cos2θ	9.5	9.5	9.6	9.7	10.1	10.4
2	cos3θ	13.0	13.0	13.1	13.3	13.8	14.3
4	cos3θ	20.0	20.1	20.2	20.5	21.3	21.9
5	cos4θ	20.3	20.3	20.4	20.7	21.5	22.2
6	cos4θ	20.5	20.5	20.6	21.0	21.7	22.4

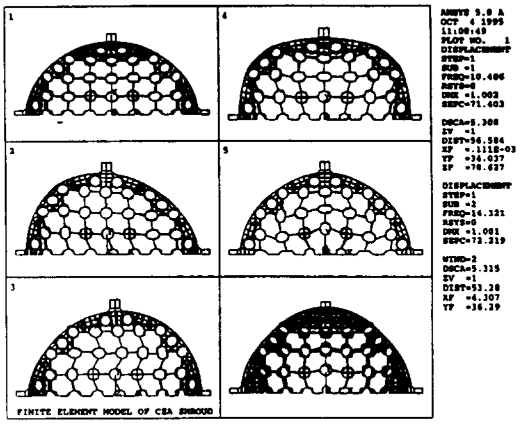

Fig. 3. Modeshapes of CEA shroud(top view)

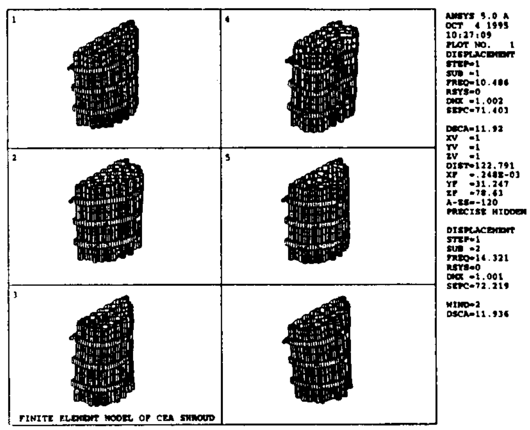

Fig. 4. Modeshapes of CEA shroud(side view)

the analysis, together with the random turbulence forcing functions, the lateral structural response is obtained. The RMS values are multiplied by a factor of 3 to produce 3σ level peak responses.

3. Measurement

The measurement was made to obtain sufficient data to confirm predictions at operating conditions of steady state and transient normal operation. This confirmation requires data related to both the flow induced hydraulic loads (forcing functions) and the dynamic response of the dynamic response of the structural components. Hence instrumentation is ncessary to measure flow and response data. The measurement was planned with adequate instrumentation to record the information necessary, with appropriate data reduction, to compare predicted and measured values of response and verify the safety margin for long term operation.

The instrumentation for the vibration measurement consisted of 2 biaxial accelerometers, 6 pressure transducers and 8 strain gages near top of the CEA shroud. Measured data from these instruments was reduced and examined for individual sensors and for sensor pairs.

The PSDs were reduced and plotted in the 0-500Hz frequency range for all instruments at all test conditions. In addition, the cross s coherence and phase were reduced and plotted in the 0-550Hz frequency range for selected combinations of instruments at all test conditions. Similar data reduction was completed and plotted for 0-50Hz. The total RMS responses found at the various instruments are tabulated in Tables 2 and 3, and are used to provide an overview of the assembly behavior as a function of temperature and number of pumps operating.

Table 2. CEA shroud measured RMS strains

(unit=micro-strain)

Temp(°F)	150	200	260		360	500		564	
Pumps[1)]	1	3	3	1	3	2	4	1	4
SG5	2.25	2.33	2.53	1.48	4.11	2.77	3.68	2.65	3.52
SG6	1.31	1.98	1.99	1.65	2.00	2.86	2.52	3.35	7.17
SG7	1.60	2.51	2.48	1.97	2.06	2.96	3.19	7.02	9.05
SG8	1.79	3.27	3.28	2.15	0.02	3.47	4.23	2.90	11.42
SG9	2.25	2.75	2.51	2.40	2.93	2.80	3.04	4.24	4.03
SG10	1.65	2.34	1.96	1.55	3.11	2.56	2.72	3.73	4.30
SG11	1.69	2.73	3.26	2.22	4.94	3.90	3.78	6.46	4.65
SG12	1.51	2.80	3.40	2.18	2.18	3.86	5.37	6.54	6.48

1) Number of pumps operated.

2) Acceptable value for strain in 200 micro-strains based on 1/3 the endurance limit of 16500 psi for 10^{11} cycle[5].

Table 3. CEA shroud measured RMS displacements

(unit=mils)

Temp(°F)	150	200	260		360	500		564	
Pumps[1)]	1	3	3	1	3	2	4	1	4
A3X	0.93	1.22	0.99	1.24	2.77	2.68	2.29	2.51	2.58
A3Y	1.18	1.50	1.36	2.27	2.92	8.36	9.11	9.71	7.30
A4X	0.84	1.21	1.06	1.59	2.61	3.43	2.61	3.42	2.86
A4Y	0.66	0.84	0.99	3.46	2.45	4.95	3.10	4.27	3.62

From the PSD distribution plots for the CEA shroud pressure transducers(Fig. 5), it is found that the random turbulence component

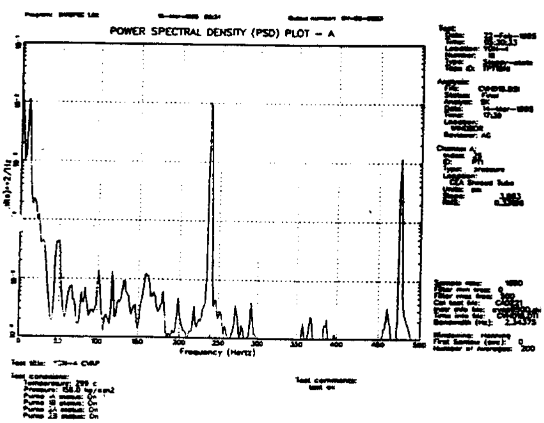

Fig. 5. CEA shroud measured response plot for pressure transducre

falls of very rapidly with frequency and levels out above a frequency of about 50Hz.

4. Results and Discussion

The response of the CEA shroud in global and assembly modes occurs at frequencies between 0 and 50Hz and individual tubes and webs respond in the 50 to 500Hz range. Table 1 and Fig. 3 and 4 show the principal assembly modes predicted to respond in the 10-22Hz range. These modes are characterized by the periphery of the assembly deforming as a shell mode cos2θ, cos3θ, etc. while the interior tubes and webs move in various complex patterns. Additional assembly modes were found in the 25-45Hz range during the analysis phase having more internal motion and a more circular exterior. Some indications of peaks in the 10-22Hz range are seen in the accelerometer data shown in Fig. 6. However, very little response is seen at these frequencies in the strain gage data shown in Fig. 7. The very low values of strain response indicate these modes are simply not being excited and the much lower than expected PSD's in the tube bank support that conclusion. The accelerometer response can be attributed to rigid body motion induced by fluid coupling between components. Evidence is seen in the data of the higher frequency assembly modes in the 25-45Hz range. These modes do not result in any significant strain or displacement.

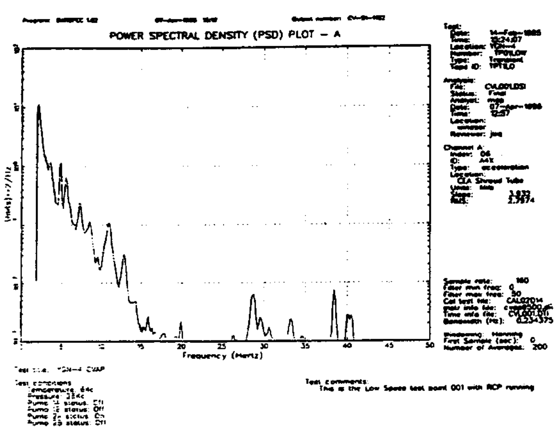

Fig. 6. CEA shroud measured response plot for accelerometer upto 50Hz

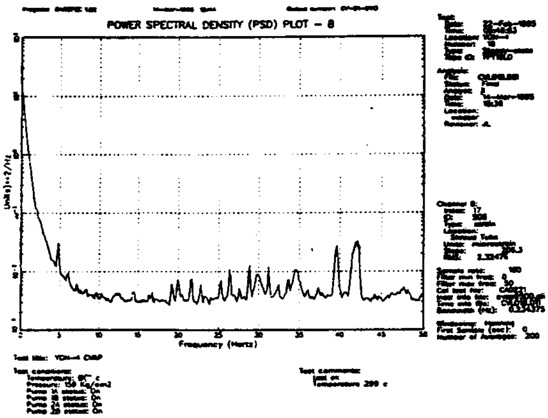

Fig. 7. CEA shroud measured response plot for straingage upto 50Hz

The response of individual tubes and webs consists principally of cos2θ and cos3θ shell modes which generally occur in the 130 to 200Hz frequency range(Table 4 and Fig. 8). The cos2θ modes, for different tube locations are predicted to have frequencies in the range of 138 through 144Hz and 178 through 186Hz. A cos3θ mode is predicted for the 193 to 201Hz frequency region. Good agreement with measured peaks is shown for all three modes by the PSD's of accelerometers(Fig. 9). Additional evidence of these modes is also shown by the PSD's of strain gages(Fig. 10).

Table 4. CEA shroud tube with 4 webs frequencies

(unit=Hz)

Mode	Shape	Temperature(°F)					
		150	200	260	360	500	564
2	cos2θ	144.2	143.6	142.7	141.2	138.8	138.0
3	cos2θ	185.7	184.8	183.6	181.8	178.7	177.6
4/5	cos3θ	201.5	200.5	199.2	197.2	193.8	192.6
6/7	cos3θ	352.0	350.3	348.0	344.5	338.7	336.6
8/9	cos4θ	499.0	496.5	493.0	488.3	480.0	477.0

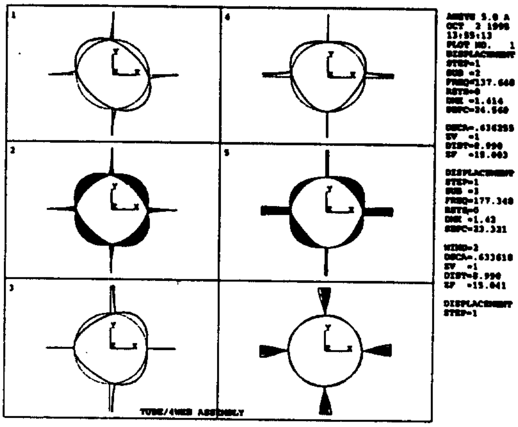

Fig. 8. Modeshapes of CEA shroud tube with 4 webs

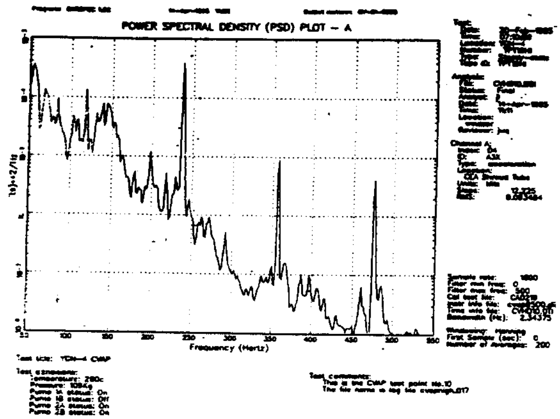

Fig. 9. CEA shroud measured response plot for accelerometer upto 500Hz

The response strains in the CEA shroud are low, as predicted. The maximum response strain was measured as 13.44$\mu\varepsilon$(micro strain) RMS. This is smaller than the maximum predicted value of 26.1$\mu\varepsilon$ and well below the acceptance level of 200$\mu\varepsilon$. This comparison of predicted and measured values is considered good.

The maximum measured value of displacement is found to be equal to 9.71 mils(Table 3). This is larger than the predicted maximum of 1.05 mils but still less than the acceptance criteria of 11 mils. The difference between predicted and measured values is considered to be the result of rigid body motion generated by fluid coupling of the core support barrel, UGS and CEA shroud components. This assumption is verified by removing the response data from 0 to 8Hz(CSB and below) from the displacement plot. The resulting RMS displacement is reduced to 1.42 mils as shown in Fig. 11. This is in line with the predictions which did not include this effect. The rigid body motion does not increase the dynamic response stress.

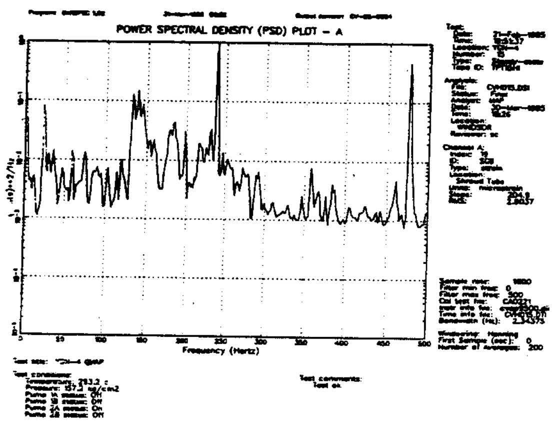

Fig. 10. CEA shroud measured response plot for straingage upto 500Hz

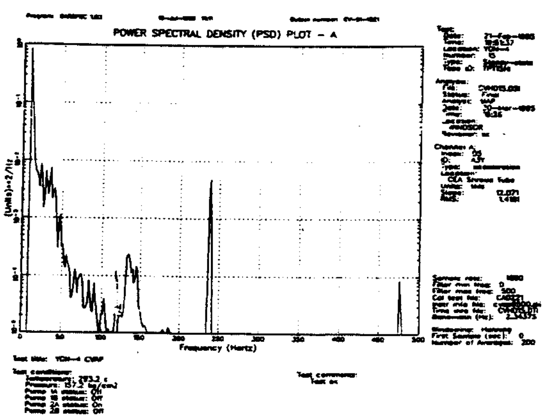

Fig. 11. CEA shroud measured response plot for 8 to 500Hz

5. Conclusions

Measured response frequencies agreed well with predicted natural frequencies and measured strains were all smaller than calculated in the prediction analysis and much smaller than the acceptance criteria. Measured displacements exceeded the maximum predicted displacements ; however the larger displacements are considered to be the result of rigid body motion generated by fluid coupling between components. The rigid body motion does not cause dynamic response stress and was not considered in the prediction analysis. All measured displacements were well under the acceptance criteria. Based on the above, it is concluded that the evaluation of the analytical predictions and measurements due to random turbulence has demonstrated the CEA shroud to be structurally adequate and acceptable for long term operation.

References

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