EK 1/5

Seismic Analysis of the Reactor Vessel for a Fast Reactor, Including Fluid-Structure Interaction

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Abstract

Two earthquake analyses were carried out, within the framework of the licensing procedure, on the reactor vessel of the German prototype of a sodium-cooled fast breeder reactor. These were carried out independently of one another, one by the consultant and one by RWTÜV. For modelling, axisymmetrical structural and fluid elements were used with non-axisymmetrical loading in the form of a Fourier series. Owing to the different theoretical bases of the fluid elements used, a comparison of results is of special interest. This comparison shows that both fluid elements are capable of describing the essential fluid-structure interaction effects. Deviations in the modal parameters and in the tertiary spectra for the component connection points lie within the usual fluctuation range for dynamic calculations.

1. Introduction

The site of the German prototype fast breeder reactor is in an area of only low seismic activity. The seismic intensity is VII and VI (MSK scale) for the safe shut-down earthquake (SSE) and operation-basis earthquake (OBE). Maximum ground accelerations taken are:

$1.2\ \mathrm{m/s^2}$ for the SSE
and $0.5\ \mathrm{m/s^2}$ for the OBE

Fig. 1 gives a general view of the installation situation of the reactor vessel system. The reactor vessel system is supported against the reactor building by support anchors and earthquake limit stops; this is done in such a way that the system can be excited into vertical and horizontal vibrations owing to base excitations.

The entire system consists mainly of structures which can be ideally represented as being axisymmetric (e.g. the tank shell, which suffers only local disturbance through the nozzles) and those which must be taken as being 3-dimensional (e.g. control rods).

During operation, the sodium covers the main vessel internals and the dip plates. For the vibrations of these parts in the case of an earthquake this means that an interaction occurs owing to the sodium present. Thus the main effects of the fluid-structure interaction must be taken into account in a calculation.

As experts consulted in the official licensing procedure, we have examined the finite element calculation submitted by the consultant by means of an independent reference calculation. The differences in modelling can be seen mainly in the use of fluid elements based on different theories. The analyses carried out can be described in brief as follows:

- axisymmetric models (shells + solids)
- 3-dimensional loading and response by expansion in Fourier series
- fluid-structure interaction algorithm
- eigenvalue calculations
- response spectrum analysis.

2. Model of calculation

2.1 Structural model

Fig. 2 shows the finite element network. With the exception of a few modifications it conforms with that of the consultant. As already mentioned, we are referring to an axisymmetrical model consisting of shell and solid elements, which takes the fluid-structure interaction into account. A two-stage calculation procedure is necessary because in this concept the response of the 3-dimensional structures can only properly be considered globally, in view of the response of the whole system. Accordingly, through the calculation for the axisymmetrical structures, internal loads are provided as a basis for the detailed stress analysis; at the same time tertiary spectra are indicated at the base points of the 3-dimensional structures as load assumptions for decoupled calculations. The consultant used the French Finite Element Program PAM-AX 3D /1/ for the analysis, whereas we used the Finite Element Program ANSYS /2/.

2.2 Fluid model

The fluid element implemented in PAM-AX 3D is derived from the basic fluid dynamic equations. In this connection the following simplified assumptions were made with regard to the fluid response:

- disregard of the viscosity
- incompressibility
- acoustic assumption

Because of the first assumption, two opposing effects are ignored in the calculation:

- additional damping of the structures due to fluid friction
- additional excitation of the structures due to the shearing stresses at their fluid-wetted surfaces

This approximation is adequate because the viscosity forces are small compared to the compression forces, owing to the low flow rates resulting from earthquake. The assumption of incompressibility means that compression disturbances propagate instantaneously, and this means the same thing as an infinite speed of sound. This approximation is adequate here because the vibration speeds are much less than those of sound, so that wave propagation processes are of no importance.

In the case of the acoustic approximation Euler's equations of movement are linearized by ignoring the convective derivations of speed.

i.e. $\frac{dv}{dt} \approx \frac{\partial v}{\partial t}$

Thus the theory is restricted to small displacements as compared with the steady state condition. This is justified because of the structural limitation of the possible sodium movements. The coupling of structure and fluid elements takes place at the interfaces via the condition of equilibrium between the compression forces and the forces of inertia. The pressure was introduced here as a further unknown variable. Furthermore, this program has a super-element technique which permits the entire fluid area to be reduced to four super-elements. Details on the theoretical basis can be found in /3/. The theory of the fluid element implemented in ANSYS is comparatively simple. It concerns a normal unit element with four nodes whose shear rigidity is taken as being almost zero. This corresponds to the effect of disregarding the viscosity in PAM-AX 3D. On account of the elastic properties of the element the compressibility of the fluid has been taken into account, which, for the reasons given above, is of no importance. At the interfaces between structure and fluid, the compatibility is produced through the displacement, as is usual with the finite element method. Unknowns which occur in the equation system here are displacement quantities. A comprehensive description of the theoretical basis of the element can be found, for instance, in the publication /4/.

3. Load input

The axisymmetrical structural and fluid elements used also permit the input of loads which are non-axisymmetrical, in the form of a Fourier series. Here the vertical excitation is represented by the zero Fourier term and the horizontal excitation is represented by the first Fourier term. The floor response spectra which are pertinent for the reactor vessel system erection site apply as load assumptions for SSE and OBE. A value of 2 % was taken into account for modal damping.

4. Calculations

Eigenvalues and mode shapes are laid down for the zero and first harmonic. The internal loads were determined according to the response spectrum analyses and the modal portions RMS are superposed. The tertiary spectra are calculated according to a method developed by the consultant. They are calculated in the frequency range directly from the floor response spectra.

5. Comparison of results

5.1 Eigenfrequencies and mode shapes

The eigenfrequencies and mode shapes are the significant system characteristics for the earthquake loads of the reactor vessel. The position of the eigenfrequencies in the floor response spectrum is decisive for the level of the related load assumption (acceleration). The structural response (e.g. displacements, acceleration, distributions of internal loads) results from the corresponding mode shape with its weighting, taking account of the load assumption.

Table I shows a comparison of the major eigenfrequencies from both calculations. In order to make a full comparison, the product of participation factor and eigenvector component is given for two structure points whose exact positions can be seen in Fig. 2. The first three mode shapes in horizontal direction and the first mode shape in vertical direction are pure fluid vibrations. Greater deviations between the two calculations can sometimes be found in the eigenfrequencies. This can be explained by the different theoretical assumptions for the fluid elements and the discretization - the consultant uses 4 super-elements only. Because of the position of the eigenfrequencies in the floor response spectrum and the very small product of participation factor and eigenvector component they make practically no contribution to the overall vibration response.

The second horizontal fluid mode shape from our calculation is shown as an example in Fig. 3. The essential structure eigenfrequencies lie between 3 and 10 Hz. The first horizontal mode shape (Fig. 4) of the whole structure is a coupled in-phase translation and rocking movement, which is determined by the support structure. The deviations in the eigenfrequencies and modal characteristics are due to different modelling of the vessel support structure. Similar deviations are also to be seen in the second mode shape of the entire system as these are also decisively determined by the support structure. Once more it is a coupled translation movement and rotational movement but now out-of-phase. In the calculation performed by us this mode shape shows a splitting of the eigenfrequencies, which is not the case in the consultant's model. The reason is also in this case an interaction of different model assumptions, it being impossible to name a single parameter as the cause. Both models give almost identical results for the eigenfrequency in connection with the vibration of the core support (Fig. 5), which is coupled with a vibration in the whole structure. There are differences in the weighting of the maximum displacements.

The results for vibrations in vertical direction display a high level of agreement for the two models. This is mainly the greater ease with which the flexibility of the vessel support system in this direction can be included. These flexibilities are mainly determined by the supporting anchors and the support ring of the vessel.

5.2 Comparison of structure loads

A detailed comparison of results is not made here because the stresses induced by safety earthquake do not exceed 10 N/mm² in most areas. The in part greater deviations in the modal parameters do not have so great an effect, and so a high level of agreement can be found.

5.3 Comparison of the tertiary spectra

Fig. 6 shows a comparison of the tertiary spectra for the node 29 (see Fig. 2) of both calculations. The deviations can be explained by the difference in the eigenfrequencies and modal parameters. The overall level of agreement can be described as good.

5.4 Stability calculations

On the basis of experience gained with the French fast-breeder reactors, buckling safety was investigated for the least favourable vessel internals, thermal shield and shielding tank. The investigations show that there is no risk to stability in the event of an earthquake.

6. Conclusions

Two independent calculations were performed to determine the seismic load for the reactor vessel system, taking account of the fluid structure interaction. Fluid elements with different theoretical assumptions were used. The results show that both fluid elements are capable of correctly describing the main fluid-structure interaction effects in the event of an earthquake. The deviations can be explained partly by the different model assumptions and are in the usual fluctuation range of structural dynamics.

7. References

/1/ PAM-AX 3D Finite Element Program for Dynamic Analysis of Axisymmetric Structures under Three Dimensional Loading, ESI 1978

/2/ ANSYS Engineering Analysis System, Rev. 4.0

/3/ I.I. Dubois, A.L. Rouvray,"An Improved Fluid Superelement for the Coupled Solid-Fluid-Surface Wave Dynamic Interaction Problem", Earthquake Engineering and Structural Dynamics 6, 235-245 (1978)

/4/ E. Wilson, M. Khalvati,"Finite Elements for the Dynamic Analysis of Fluid-Solid Systems" Int. J. num. Meth. Engng 19, 1657-1668 (1983)

TABLE I: COMPARISON OF EIGENFREQUENCIES AND MODAL PARAMETERS

Direction of Oszillation	Eigenfrequency [Hz]		Participationsfactor x Eigenvektor-Component				Main Mode Characteristics
			Nodal Point 29		Nodal Point 219		
	Consultant	RWTÜV	Consultant	RWTÜV	Consultant	RWTÜV	
Horizontal	0,27	0,68	0	-0,003	~ 0	~ 0	Fluidmovement
	0,44	1,06	0,0004	0,029	~ 0	0,003	Fluidmovement
	1,21	1,23	0	-0,001	~ 0	~ 0	Fluidmovement
	3,75	3,26	1,070	1,140	0,206	0,072	Structure
	4,81	4,60	0,604	0,284	0,188	0,023	Core Support
		9,30		-0,284		0,212	Structure
	7,9		-0,744		0,555		
		10,30		-0,412		0,571	
Vertical	1,2	1,00	0	0	0	0	Fluidmovement
	5,29	4,70	0	0	0	0	Fluidmovement
	7,51	7,89	1,081	1,072	1,020	1,041	Structure

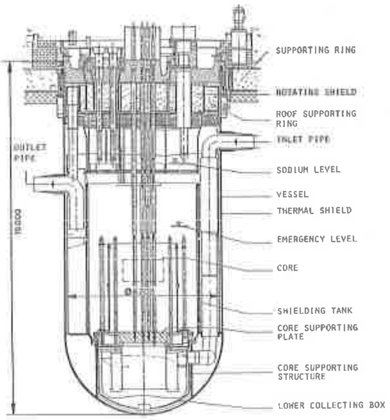

Figure 1
Reactor Vessel

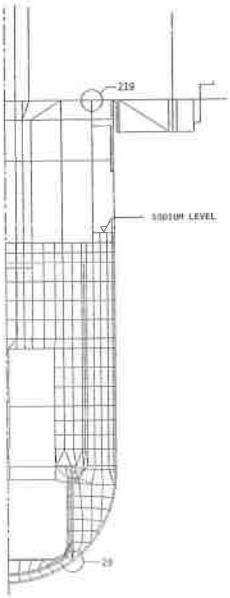

Figure 2
Finite Element Mesh

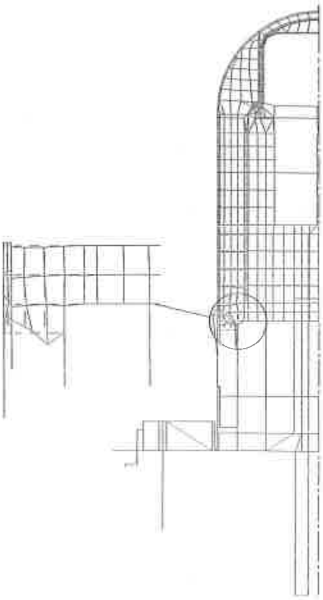

Figure 3
Fluid Mode, F = 1,06 Hz

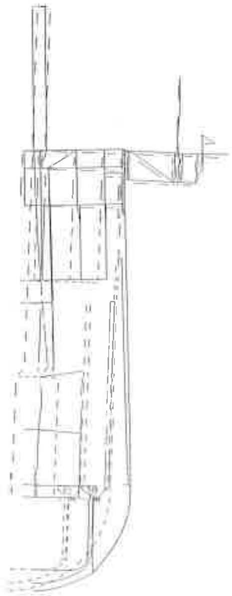

Figure 4
First Structural Mode, F = 3,26 Hz

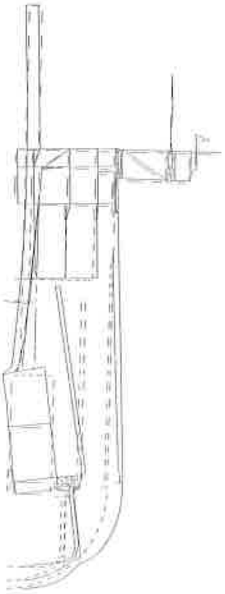

Figure 5
Second Structural Mode (Core), F = 4,6 Hz

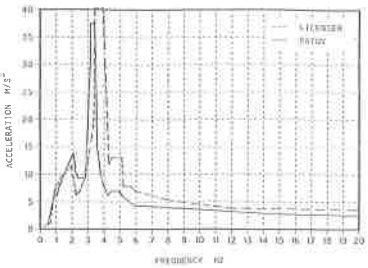

Figure 6
Tertiary Spectrum (SSE) of Node 29