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SEISMIC ANALYSIS OF FAST BREEDER REACTOR BLOCK

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ABSTRACT

Seismic analysis of LMFBR reactor block is complex due mainly to the fluid structure interaction and the 3D geometry of the structure. Analytical methods which have been developed for this analysis will be briefly described in the paper and applications to a geometry similar to SPX1 will be shown.

INTRODUCTION

Seismic analysis of a Loop type Fast Breeder Reactor is usually carried out in two phases. The first one is related to the analysis of the building taking into account soil-structure interaction and the internal structures which must be, in this first calculation, represented by a simple model. In the second phase a detailed analysis of the internal structure behaviour is performed ; the external loading is given by the basemat motion calculated in the previous step. The aim of the paper is the presentation of methods developed for this second phase.

Internal structures of a LMFBR reactor such as SUPERPHENIX (see Fig. 1, 2) are composed of axisymmetrical shells separated by fluid volumes. But the complete geometry is not axisymmetric due to the components (heat exchangers and primary pumps) and to communications between the various fluid volumes (in addition to large fluid communications related to the components there are very small passages between the fluid volumes).

In the various sections of this paper the methods to study these internal structures and the application to a geometry similar to SUPERPHENIX will be presented. The description of the axisymmetric modelization which is used for design calculation is followed by a short presentation of the method to take into account fluid structure interaction. Then the equivalent element to fluid passage will be described. Finally the method, based on substructuration to represent the 3D geometry will be detailed.

AXISYMMETRIC MODELIZATION

The seismic analysis of LMFBR internal vessels is usually performed with axisymmetric models of the vessels and of the fluid. In this model shell finite elements describe the vessels. The components can be represented by equivalent oscillators defined from their modal analysis (Ref. 1).

Fluid structure interaction couples the various shells and no fluid coupling is taken between the components or between the components and vessels. The equations of the fluid structure system can be written for mode calculations, when neglecting the compressibility of the fluid (for the general equations see Ref. 2) :

$$\left\{ \begin{bmatrix} K & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_Z \end{bmatrix} - \omega^2 \begin{bmatrix} M & -M_C^T & 0 \\ -M_C & -M_L & -M_Z^T \\ 0 & -M_Z & 0 \end{bmatrix} \right\} \begin{bmatrix} d \\ \pi \\ Z \end{bmatrix} = 0$$

where d is the vector of the shell displacements
π is a vector associated to the pressures ($\pi = -\omega^2 p$)
Z is the vector of the free surface displacement

Validation of this method has been performed by comparison to analytical solution and to experimental data.

By example, the free surface mode of a cylindrical tank (Radius = 1.429 m - Height = 1.039 m) containing water which can be excited by horizontal seismic motion (cos θ : harmonic variation) has a calculated frequency equal to 0.53 Hz which is in very good agreement with analytical solution (Ref. 2).

An other example of validation for axisymmetric structures is the study of a cylinder which has a translation motion. It is coupled by fluid to an external motionless cylinder (Ref.3). The evolution of the first frequency with the water level obtained by calculation and test is reported on Figure 3.

For LMFBR reactor block analysis with an axisymmetric model, the modes which contribute to seismic response (cos n θ : n = 0 for vertical seism, n = 1 for horizontal seism) can be separated in two families :

- free surface modes for which the shells are motionless. These modes are important mainly for the calculation of the free surface motion ;
- modes with shell motion and then, shell coupling induced by the fluid. These modes can be calculated with a zero pressure condition on the free surface as it is shown in Ref. 4 and on the following LMFBR analysis.

The harmonic n = 1 natural modes of a block reactor, similar to SPX1, were calculated with the finite element mesh given on Figure 4. This mesh is defined by 236 shell elements, 446 fluid elements and 828 nodes and takes into account the internal vessels, the fluid volumes, the core but also the safety vessel and the dome. The structure is clamped at the basemat level.

Comparison of the mode characteristics obtained with the free surface variables (Z) and with zero pressure condition on the free surface are reported on Table 1. One can notice the good agreement on the frequencies and the modal masses for the modes where fluid structure coupling is important (see also Figure 5, where mode shapes have been drawn).

The comparison of seismic response calculated with the two conditions for the free surface shows a discrepancy smaller than 5 %.

FLUID COMMUNICATIONS

The axisymmetric shells of LMFBR are currently separated by fluid volumes which are connected one to another by small communications. These communications destroy the axisymmetry of the problem and in addition, a correct modelization by finite element method generally needs a lot of small elements compared to the size of the fluid volumes standard mesh and is not applicable.

To overcome these difficulties, an equivalent axisymmetric element based on a local tridimensional solution in the vicinity of the fluid communication was defined. After a short description of this element which is characterized by an equivalent length and annular cross-section, the application to FBR vessels will be presented.

The influence of a fluid communication is essentially due to the inertial effect if the fluid can be assumed to have a linear and incompressible behaviour. This effect is characterized by an impedance, I, which can be realized as in a plane wave model by an equivalent fluid column with the same cross section S of communication and an equivalent length ℓ. I is defined by the ratio of the fluctuating pressure gap due to the communication and the fluctuating mass flow rate. It is deduced from the resolution of Laplace equations in the volume near the ends of the communication.

First, calculations were performed for various communications which can be found in FBR structures : various sizes and various geometries (annular, circular ...). Curves giving the equivalent length, ℓ, was then established as shown on Figure 6 for horizontal seismic calculation (n = 1) in case of an annular communication in an annular volume.

To avoid a mesh with many small axisymmetric elements, a procedure was developed in order to keep the standard mesh, adapted to the global fluid structure, and to introduce an equivalent fluid connection element which represents the local inertial effect of the communication.

This equivalent element has the section of the standard finite element, S_m, and then its equivalent length, ℓ_m, calculated by conservation of the impedance, is equal to :

$$\ell_m = \frac{S_m}{S} \ell$$

The influence of fluid communications was studied on the reactor block described previously. The calculation without communications and with zero pressure condition for the free surface is the reference calculation.

Three types of fluid communication have then been studied (Fig. 7) :

(1) Communications (1) and (2) between a large fluid volume and a thin fluid sheet.

(2) Communication (3) between a large fluid volume and a large fluid sheet.

(3) Communication (4) between two thin fluid sheets.

The modal analysis with these models in the 0, 10 Hz frequency range shows an important redistribution of modal masses and a strong modification of the associated fluctuating pressure fields. A communication at the end of a fluid sheet changes the associated boundary conditions of the fluid, so the inertial effects are modified (generally decreased). The greatest influence occurs on the modes associated to the lowest frequencies, as these modes are strongly influenced by fluid pressure in the fluid sheets (the mode shape is slightly changed (see Figure 8), but the resonance frequencies increase and generalized masses decrease).

The comparison of the seismic responses calculated with the various communications and with the reference geometry shows :

- a very weak influence of the communication n° 3 ;
- an important effect of the communication n° 1 on the vertical displacement of the baffle B1 and of the two redans ;

- an important variation of the main vessel motion, especially for the communication n° 2. This effect can be explained by the redistribution of the modal masses between closely spaced modes ;

- a great modification of the pressure field for the shells at the vicinity of the fluid communication.

These results indicate the necessity of the communication modelization as they modify the shell motion but also the pressure and in consequency they are important for the buckling under seismic loading.

3D MODELIZATION

FBR internal structures are three dimensional due to the components, so it is necessary to make 3D dynamic calculations.

For 3D structure composed of axisymmetric structures, a substructuring technique is very efficient if substructures are defined by their natural modes calculated with free boundary conditions at all connection nodes.

Mechanical coupling between substructures is achieved by assembling them with link forces located at the connection nodes. The effect of neglected modes is introduced by a flexibility matrix deduced from static responses to forces located at each connection node.

This procedure generally leads to economic calculations, especially when some substructures are axisymmetric as their natural modes have harmonic variations (cos $n\theta$ or sin $n\theta$) and only need a 2D model (Ref. 6).

In structures similar to FBR ones, two types of fluid-structure interaction can be distinguished : axisymmetrical fluid-structure interaction (shell-sheet) which can be taken into account in the substructure calculations and fluid coupling between the substructures which can be calculated as a special inertial coupling.

Finally, for FBR internals where substructures are coupled by mechanical links and by a fluid, we obtain the following system (for details, see Ref. 7) :

$$\begin{bmatrix} K_G & B^T & 0 \\ B & -S & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \alpha \\ F \\ \bar{\pi} \end{Bmatrix} + \begin{bmatrix} M_G & 0 & -I \\ 0 & 0 & 0 \\ -I & 0 & -Q^{-1} \end{bmatrix} \begin{Bmatrix} \alpha'' \\ F'' \\ \bar{\pi}'' \end{Bmatrix} = \begin{Bmatrix} f_e \\ 0 \\ f_f \end{Bmatrix}$$

The system variables are the modal contributions, α ; the connection variables are the link forces, $\bar{F}$, and the generalized fluctuating pressure forces, $\bar{\pi}$.

The generalized stiffness matrix, K_G, and mass matrix M_G are diagonal.

The generalized added mass matrix Q, which is obtained by added mass matrix projection on the natural modes, is symmetric and its size is equal to the number of modes or to the number of form functions used to describe the shell motion.

Practically, the application of this method needs four steps :

- calculation of substructure modes,
- calculation of the matrix S, due to truncation, by static solutions to forces,
- calculation of the added mass Q by solution of Laplace equations,
- calculation of the connected structure.

This method was applied to a reactor block similar to SPX1 (Ref. 8).

In addition to the vessels, eight heat exchangers and four primary pumps (and their crossings) are located unsymmetrically around the core and are coupled to the thin shells both mechanically and by the sodium of the hot collector. These components are composed of axisymmetric shells. Due to symmetry only a quarter of the structure is modelized and it is divided into the following axisymmetric substructures :

(1) Heat exchanger, its two crossings, internal sodium volumes and sodium sheets.
(2) Primary pump, its two crossings, internal sodium volumes and sodium sheets.
(3) All the other structures of the reactor, sodium volumes and sodium sheets except the sodium volume of the hot collector.

The hot collector has a strong 3D geometry and couples the different above-mentioned structures. So this fluid volume is taken into account with the previously described method.

The system to solve for such a couplex geometry has more than 700 unknowns : the third substructure is represented by 246 modes with frequency lower than 20 Hz and azimutal variation lower than 19 (only odd numbers were studied due to the symmetry). The pump is represented by 44 modes and each heat exchanger by 68 modes. There are 210 mechanical links between components and vessels and the generalized added mass matrix is a 77 x 77 matrix, because we use 77 form functions to describe the inner vessel and the component motions.

All the modes with frequencies lower than 10 Hz have been calculated for the complete structure. We have found a very big density of modes : 159 modes. The lowest frequency, equal to 0.33 Hz, corresponds to a movement of the conical redan shroud (with mainly an azimuthal variation in cos 3θ) and a small movement of the conical redan with rigid body motion of the primary pumps external crossing.

The analysis of the complete structure modes shows that they are, in general, composed by :

- many basis modes (until 50) of the substructure (3).
- several modes of the components crossings. The complexity of the modeshapes increases with the frequency and indicates strong 3D features (see Figure 9). This phenomenon is due both to the mechanical and fluid coupling between all the substructures.

The modal analysis was compared to an equivalent analysis that we have carried out on a 2D classic modelization such as described previously with in addition oscillators to represent the components. The comparison with the 3D calculation shows that the modes with important modal masses are located in the same frequency ranges, but, in the 3D case, they are more numerous and each of them includes not so much modal mass.

The seismic analysis has been performed using the response spectrum method, but the usual SRSS method is not acceptable because the natural frequencies of the system are closely spaced (modal responses are not statistically independent). So, we used the double sum combination method (DSC) (Ref. 9 - 10) which takes into account the cross-correlations between the modal components.

The 3D calculation shows a strong 3D aspect of the seismic response (displacements - stresses or pressures). Nevertheless, the discrepancy between the 2D and 3D responses does not exceed 30 % and generally the 3D response is lower than the 2D response. For few variables the 2D calculation is underconservative.

In conclusion, the 2D model remains a very useful tool at the beginning of the design of LMFBR, but final verification must be performed with a 3D model.

CONCLUSION

Methods have been developed for the LMFBR seismic analysis and applications to structures similar to SPX1 has demonstrated the influence of gravity, fluid communications and components. The applications have shown that, when increasing the details of the modelization, the number of modes increases and many modes with small frequency differences appear. The usual SRSS mode combination is then no more acceptable and mode coupling has to be taken into account.

The research program which is now undergoing on the LMFBR seismic analysis is performed in the framework of european research and is associated to EFR reactor (Ref. 11). It is related to the experimental validation of the available methods and to the definition of simplified methods which could be applied to various designs of the vessels. In addition, a methodology to define the most severe pressure fields to introduce for the buckling analysis avoiding, if possible, the time history analysis has to be studied. Finally, some work has to be performed on the criteria taking into account the dynamic characteristics of the seismic loading.

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	With free surface variables		With zero pressure conditions	
No	Freq. (Hz)	M (T)	Freq. (Hz)	M (T)
1	0.07	3		
2	0.11	34		
3	0.14	22		
4	0.18	755		
5	0.21	134		
6	0.36	88		
7	0.47	3		
8	0.58	8		
9	0.62	37	0.57	40
10	0.67	0		
11	0.77	2		
12	0.86	0		
13	0.87	1	0.82	1
14	0.96	1		
15	1.06	0		
16	1.16	1		
17	1.26	0		
18	1.35	0		
19	1.40	0		
20	1.44	0		
21	1.90	155	1,90	156
22	2.20	175	2.10	170
23	2.28	260	2.27	201
24	2.31	19	2.30	76
25	2.59	159	2.59	160
26	2.70	2		
27	3.06	1	3.04	0
28	3.18	95	3.16	96
29	3,86	406	3.85	395
30	4.29	5		
31	4.48	2845	4.48	2815
32	4.80	2		
33	5.24	3252	5.23	3280
34	5.39	673	5.39	679
35	6.80	99	6.80	96
36	7.14	367	7.13	370
37	7.21	300	7.21	302
38	7.27	1011	7.27	1004
39	7.97	1025	7.97	1016
40	8.40	2433	8.39	2439
41	8.97	169	8.96	171
42	9.21	9	9.21	9
43	9.71	9	9.71	9

- TABLE 1 -

NATURAL MODES FOR REACTOR BLOCK ANALYSIS UNDER HORIZONTAL SEISM

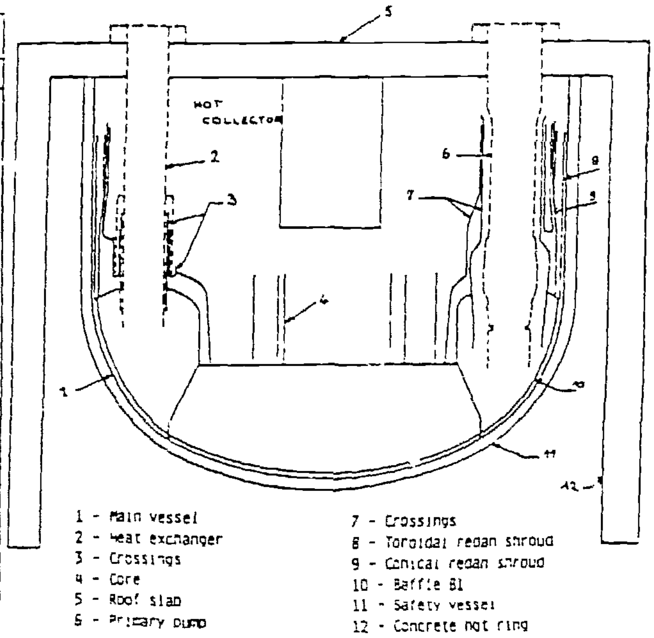

Fig. 2 - LMFBR INTERNALS

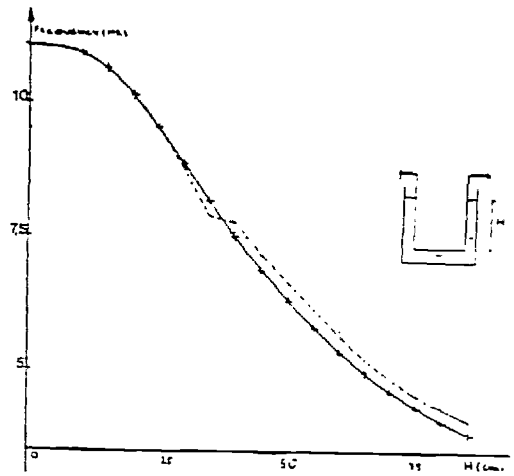

Fig. 3 - FREQUENCY AS A FUNCTION OF WATER LEVEL

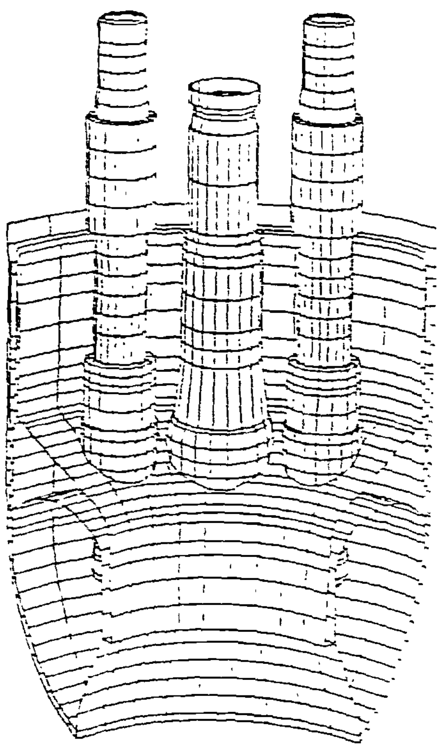

Fig. 1 - LMFBR INTERNALS

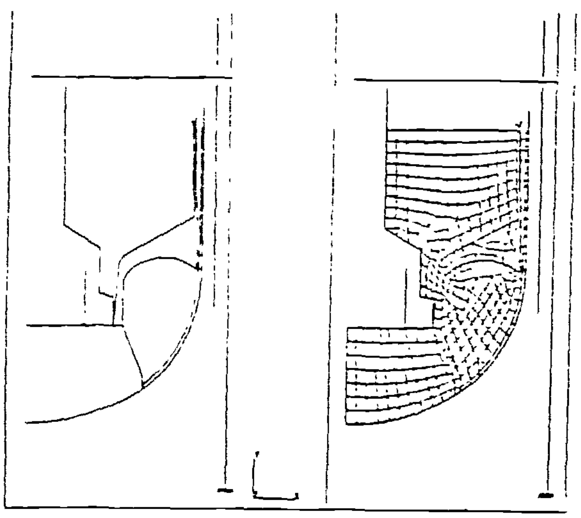

Fig. 4 - SHELL MESH FLUID MESH

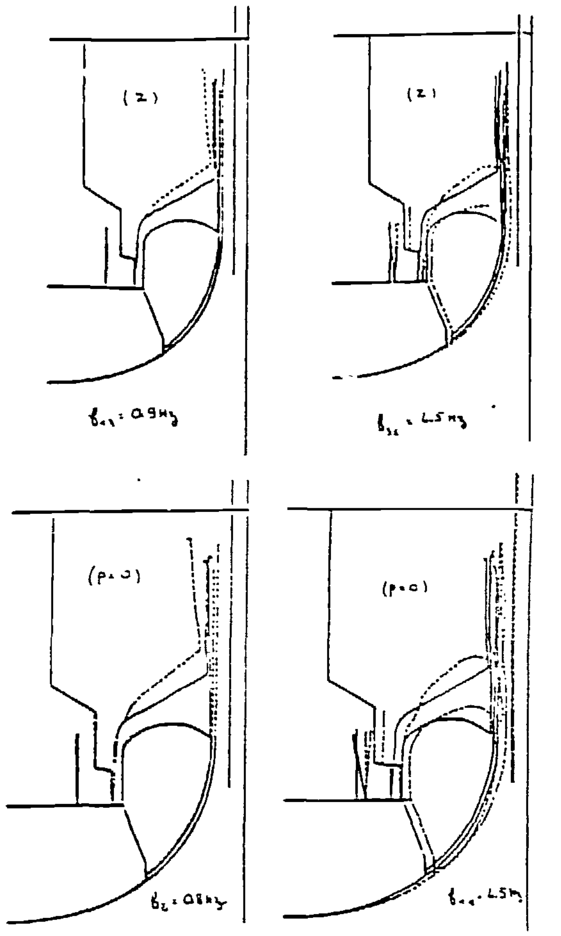

Fig. 5 - MODE SHAPE WITH AND WITHOUT FREE SURFACE VARIABLES

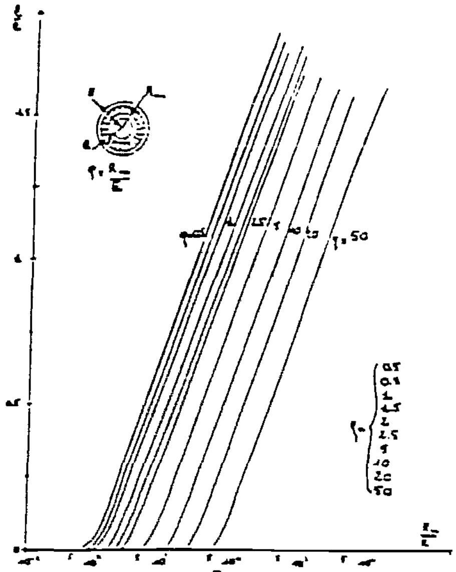

Fig. 6 - EQUIVALENT LENGTH, ℓ, OF FLUID COLUMN FOR ANNULAR HOLE IN ANNULAR CAVITY (n = 1)

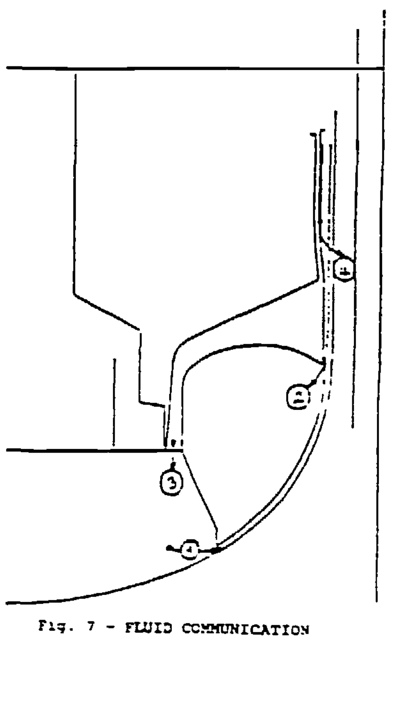

Fig. 7 - FLUID COMMUNICATION

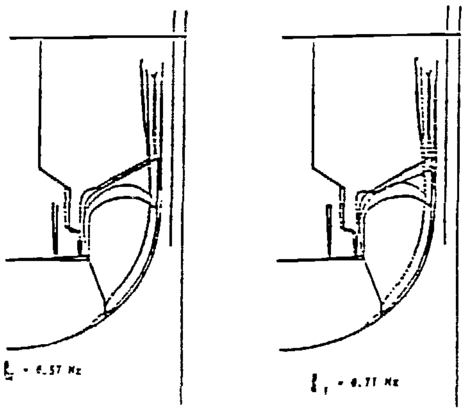

Fig. 8 - MODE SHAPE WITHOUT AND WITH FLUID COMMUNICATION

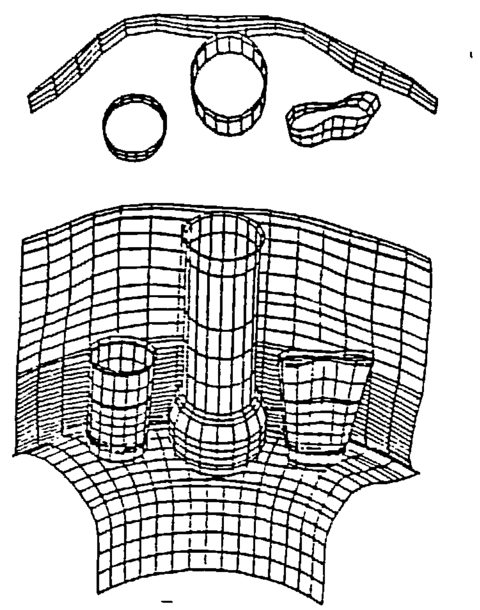

Fig. 9 - 3D MODE SHAPE - f = 5.0 Hz