Seismic Analysis of Large Components Inside the Pool of a LMFBR

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Summary

For the seismic analysis of a FBR pool type reactor vessel, simplifications are made and structures are assumed to be axisymmetric. Components like pumps and intermediate heat-exchangers are represented by equivalent structures. Therefore a detailed analysis must be made separately with a multiple support technique applied to a structure immersed in a fluid. This paper presents the method used for the dynamic analysis of some large components of a pool type LMFBR.

The analytical formulation underlying the method is described for time history or response spectrum method. Included are the effect of high frequency modes or left out masses.

A complete investigation involve the following steps :

1 - Static analysis for modal participation factor and residual modes calculation
2 - Modes shape and eigenfrequency determination
3 - Response calculation

In most cases step 1 can be deleted. Three examples of analysis are presented.

Problem 1 Core cover plug behaviour under vertical seismic motion. This structure can be described as a cylinder attached to the upper deck, and holding the above core shield plate. Main source of seismic excitation is the differential displacement between the upper deck and the sodium.

Problem 2 Primary pump response under horizontal seismic motion.

Pumps are simply supported on the upper deck and are connected at the lower end to the core support structure. Detailed calculations are made with an axisymmetric model using as input horizontal motion of the upper deck, core support structure, inner vessel and fluid.

Problem 3 Intermediate heat-exchanger IHX are flexible structure clamped to the upper deck with no mechanical links with the reactor inner vessel. Seismic displacement of the IHX support must include the rocking motion induced by the vertical displacement of the upper deck.

As a conclusion, detailed seismic analysis of large components in the pool of a sodium cooled reactor are feasable when taking into account the fluid effect on dynamic properties and seismic excitation transmission.

1. Introduction

The vessel of pool type reactor contains structures like pumps and intermediate heat-exchangers(IHX) which require a detailed seismic analysis. This can be done in two steps, using first the global reactor seismic model, the motion at the supports or structure boundaries is obtained, then a detailed analysis of the components is performed. Fluid effect must be taken into account in the calculation of the dynamic properties of the whole system, as well as in the determination of the seismic forces.

This paper :

- describes the general mathematical formulation applicable for linear structure in the presence of fluid,
- gives three examples of application.

2. Mathematical formulation

2.1. Equation of motion

The theory of multiple support excitation analysis is well established, if the model is built with no mass at the support points the equations are : (Réf. 1)

$$\begin{vmatrix} M & 0 \\ 0 & 0 \end{vmatrix} \begin{vmatrix} \ddot{X}_A \\ \ddot{X}_G \end{vmatrix} + \begin{vmatrix} K & K_G \\ K_G^T & K_{GG} \end{vmatrix} \begin{vmatrix} X_A \\ X_G \end{vmatrix} = \begin{vmatrix} 0 \\ F \end{vmatrix} \quad (1)$$

at this stage damping is neglected. Using the added mass formulation described in Réf. (3) the fluid introduces non diagonal elements in the mass matrix M.

X_A and X_G are absolute displacements respectively for unconstrained and support degrees of freedom.

Further the problem is assumed to be linear. Using the transformation

$$X_A = X + RX_G$$

with the matrix $R = -K^{-1}K_G$

The set of equations is written as :

$$M\ddot{X} + KX = -MR\ddot{X}_G \quad (2)$$

$$F = R^T M \ddot{X}_A - \left| K_{GG} - R^T K R \right| X_G \quad (3)$$

Equation (2) is the dynamic equation of the structure with fixed support points. Such an equation is commonly used in the standard seismic analysis of a structure with a base moving in translation, in that case R is a vector of units and zeros and the last term of equation (3) vanishes.

2.2. Modal analysis

Mode shapes and frequencies are solution to the generalized eigenvalue problem

$$K\Phi = M\Phi\Omega^2 \quad (4)$$

Ω^2 is a diagonal matrix of the eigenvalues ω^2 (circular frequencies squared). The columns in $\emptyset$ are the eigenvectors. With the normalization

$$\phi^T M \phi = I \qquad \phi^T K \phi = \Omega^2$$

The participation factor matrix is : $\Gamma = \phi^T M R$
and contains N columns each corresponding to one support degree of freedom.

Let : $X = \emptyset\, Y$ then the uncoupled equation of motion for any particular mode is :

$$\ddot{y} + 2\varepsilon\omega\dot{y} + \omega^2 y = -\sum_N \Gamma_N \ddot{X}_{GN}(t)$$

Modal damping has been reintroduced, it can be computed by the strain energy weighting method (see Réf. 2).

2.3. Time history analysis

Modal displacements Y can be expressed using the DUHAMEL integral

$$V_N(t) = \int_0^t \ddot{X}_{GN}(t) \exp\left[\varepsilon\omega(t-\tau)\right] \sin\omega_D(t-\tau)\, d\tau \qquad \omega_D = \omega\sqrt{1-\varepsilon^2}$$

$$y(t) = -\sum_N \frac{\Gamma_N V_N(t)}{\omega}$$

and for small values of damping

$$\ddot{y}(t) = \sum_N \Gamma_N \left[\omega V_N(t) - \ddot{X}_{GN}(t)\right]$$

at high frequency, for rigid modes

$$\omega V_N(t) \rightarrow \ddot{X}_{GN}(t) \quad \text{then} \quad \ddot{y} \rightarrow 0$$

Using matrix notation and dropping the summation sign $\sum$ for simplicity we have :

$$X_A = \phi y + R X_G = -\phi \left|\frac{\Gamma V(t)}{\omega}\right| + R X_G(t) \qquad (6)$$

$$\ddot{X}_A = \phi \ddot{y} + R \ddot{X}_G = \phi \left|\Gamma\omega V(t)\right| + \left|R - \phi\Gamma\right| \ddot{X}_G(t) \qquad (7)$$

It can be shown that if the number of modes is equal to the number of degrees of freedom (D.O.F) of the mass matrix then $|R - \emptyset\Gamma|$ is null for these D.O.F.

For large size problems it is usual to extract only the first significant eigenvectors and to delete the remainding $\emptyset_L$. However if $\emptyset_L$ correspond to rigid modes, their response is

$$\phi_L \left|\Gamma_L \omega V(t)\right| = \phi_L \left|\sum_N \Gamma_{LN} \ddot{X}_{GN}(t)\right|$$
$$= \phi_L \Gamma_L \ddot{X}_G(t) = \left|R - \phi\Gamma\right| \ddot{X}_G(t)$$

Which is the last term of equation (7), consequently in the acceleration calculation no error is introduced by deleted modes.

This suggest to obtain the structure deformation from the inertial loading that is :

$$X = K^{-2} M \ddot{X}_A$$

making use of equation (4) and after reordering

$$X_A = -\phi\left|\frac{\Gamma V(t)}{\omega}\right| - \left|D - \Omega^{-2}\phi\Gamma\right| \ddot{X}_G(t) + R X_G(t) \qquad (8)$$

$D = K^{-1} M R$ is the structure deformation under loading MR.

Compared to equation (6), (8) contains one more term.

Forces applied to the structure at support points are derived from equation (3)

$$F = \Gamma^T Y + R^T M R \ddot{X}_G + |K_{GG} - R^T K R| X_G$$
$$= \Gamma^T |\Gamma \omega V(t)| + |R^T M R - \Gamma^T \Gamma| \ddot{X}_G(t) + |K_{GG} - R^T K R| X_G(t) \qquad (9)$$

Here again the second term in the right hand side of equation (9) vanishes if all the modes are present.

2.4. Residual modes, left out masses

With the above three equations, there is no need to extract modes above a cut-off frequency which depends of the input signal (33 Hz is a standard value for seismic analysis). The second term of these expressions gives the influence of the higher modes of structure deformation and it is convenient to use the denomination of :

- "residual modes" in the calculation of accelerations and displacements, one for each support point D.O.F.
- "missing masses" in the determination of forces applied to the structure at N support points (N x N matrix).

2.5. Response spectrum method

In multisupport modal analysis a double summation appears, namely on supports and on modes. The time history method is expensive and a simplification is introduced by the response spectrum method which uses only the maximum of each term in the sum.

A spectrum is defined for each support motion, giving the maximum of the DUHAMEL integral, and for large values of ω , the maximum of $\ddot{X}_{GN}$ (t).

$$Sa(\omega) = \text{MAX}\left[\omega V_N(t)\right]$$

Then a summation rule must be choosen.

At ground level the three spacial components of seismic excitation are assumed to be statiscally independant and it can be supposed that they are separetely analysed. Therefore the support motions are dependant and for each mode their effects must be added arithmetically. The modal superposition is carried out afterwards : the quadratic sum method is generally used, it assumes a random phase relationship between modes, but a special rule may be requested for closely spaced modes.

Above the cut-off frequency the modes are not independant and the order of summation must be reversed. First an algebraic superposition of modes is made for each support motion then the effects of different supports are added arithmetically. Let us remark that this procedure corresponds exactly to what is done when using residual modes.

In a final step the three dimensional earthquake effects are combined quadratically.

Expression (9) may be helpful to obtain the participation factors of each support. If a rigid body motion producing a displacement I_S for each D.O.F., is given to the support points, then a standard seismic analysis is performed. The modal participation factor is :

$$\Gamma_S = \sum_N \Gamma_N I_S$$

For a unit spectral acceleration the vector of modal support forces if F and :

$$\Gamma^T = F \times \frac{1}{\Gamma_S}$$

3. Application to components

In the examples given below, the time history method has been used. The participation factors has been derived from the forces applieds at the support points, for that purpose the fluid has been bounded by mechanical elements which act like springs.

The input motion is obtained by a time history analysis of the reactor vessel. At the base level two independant artifical time histories has been used with three differents time steps.

3.1. Core cover plug

This structure can be described as a cylinder attached to the upper deck and immersed in sodium. At the bottom it is closed by the above core shield plate (Fig. 1).
The fluid element (Fig. 2) takes account of communications between fluid volumes.

A vertical motion is applied to the upper deck (1) and to the lower boundary of the fluid (2).

Frequencies N (Hertz) and participation factors Γ_1 (upper deck) and Γ_2 (fluid) are given below for the first modes.

MODES	1	2	3	4	5	6
FREQUENCY	6,51	8,89	9,98	24,7	36,4	44,2
Γ_1	53,3	64,6	48,7	- 5,1	- 34,5	- 42,6
Γ_2	- 55,8	- 39,5	- 20,8	388,9	- 9,6	- 10,3
Γ_V	- 2,5	25,1	27,9	383,8	- 44,1	- 52,9

$\Gamma_V = \Gamma_1 + \Gamma_2$ is the participation factor obtained in the dynamic analysis. This example shows that the main source of excitation for the first mode is the differential displacement between the upper deck and the fluid. The calculated shield plate deflection is 3 to 4 time this relative displacement.

A standard seismic analysis would underestimate this value.

3.2. Primary pump

The pumps are supported on the upper deck by an elastic ring and are connected at the lower end to the core support structure. Each pump is surrounded by two cylindrical shells attached to the reactor inner vessels (Fig. 3).

For the calculation an axisymmetric model has been used and fluid added around the shells to simulate the sodium inside the reactor vessel.

Five horizontal input motions are applied (Fig. 4)

1 - upper deck
2 - upper external fluid
3 - cylindrical shells
4 - lower external fluid
5 - core support structure

20 modes have been used from 2 to 90 Hz.

Participation factors are given below for the first three modes.

FREQUENCY	Γ_1	Γ_2	Γ_3	Γ_4	Γ_5	Γ_H
2,1	0,2	- 75,8	91,2	- 8,6	0,3	7,2
5,3	70,4	2,5	- 74,1	- 5,1	138,9	132,5
9,6	2,6	32,8	- 107,5	37,5	- 14,3	- 49,0

In the acceleration calculation the vector R has only two non zero terms corresponding to motions 1 and 5. On the lower pump bearing, the maximum acceleration is less than twice the value obtained for the core support structure.

3.3. Intermediate heat exchanger

The IHX is surrounded by two cylindrical shells attached to the reactor inner vessel (Fig. 5).

Five input motionsare applied (Fig. 6) 1 to 4 are the same as for the pump, 5 is the upper deck rocking induced by the vertical seismic excitation.

Fifteen modes has been used. Participation factors are given below for 3 significant modes

FREQUENCY	Γ_1	Γ_2	Γ_3	Γ_4	Γ_5	Γ_H
2,1	140	- 39	- 9	- 38	- 1 369	53,7
15,0	68	- 9	2	19	51	79,7
22,4	102	- 2	2	- 6	138	97,4

Differential displacement between the IHX and cylindrical shell is 3,4 cm for OBE conditions and 4,7 cm for SSE.

4. Conclusion

Seismic analysis is feasible for complex components immersed in fluid, using multi-support excitation technique and time history or response spectrum method.

Fluid can affect the dynamic properties of the structure and transmit the seismic motion.

The use of "résidual modes" or "missing masses" has been established on a rational basis, giving the condition to derive exact results.

The examples of application suggest that in some instance, a single support technique with envelope spectra, may underestimate the response of a structure.

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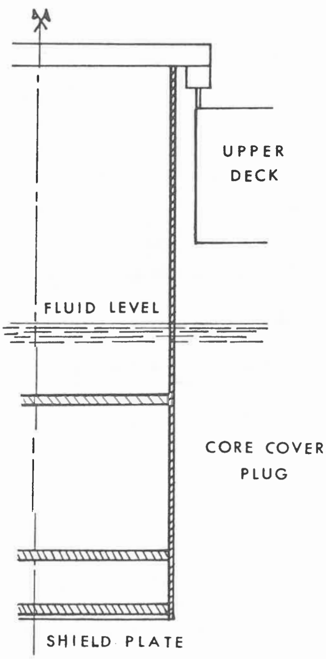

FIGURE 1

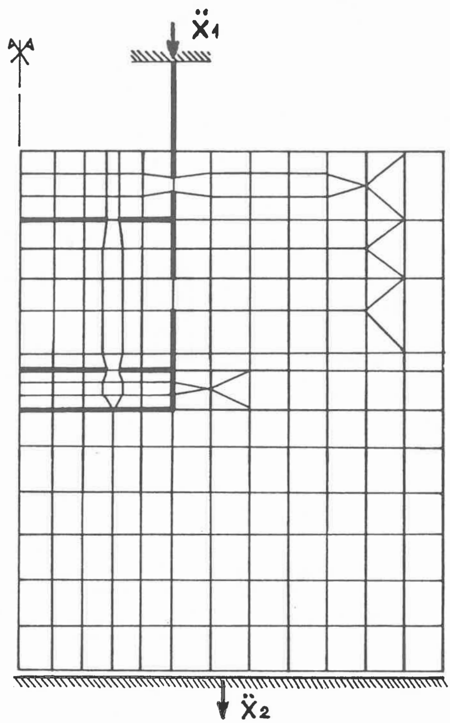

FIGURE 2

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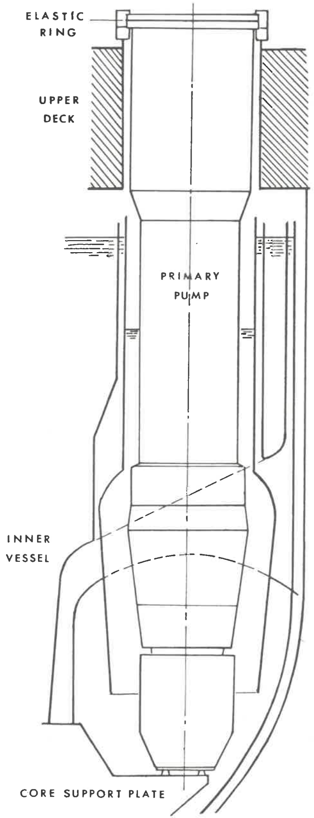

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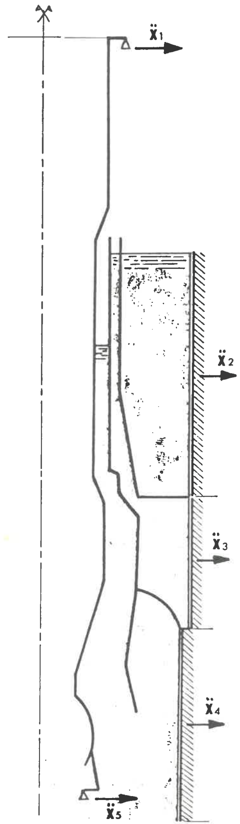

FIGURE 4

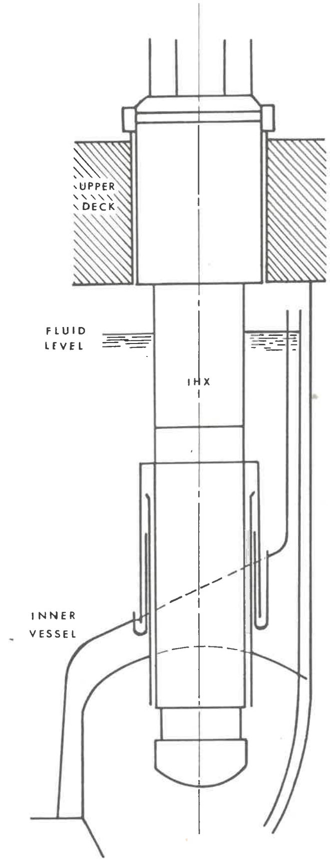

FIGURE 5

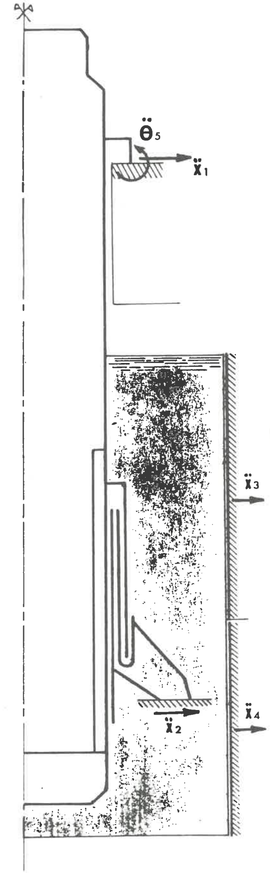

FIGURE 6