On the Influence of the Fluid on the Seismic Response of FBR Cores

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1. BACKGROUND

Up to now, the seismic analysis of FBR cores has always been performed ignoring the effect of fluid altogether, or, if it did not, using a gross approximation involving only an added mass to individual subassemblies and an increased modal damping.

Using that approach is known to be very conservative and, in fact, it led to difficulties in fulfilling the design requirements. More specifically, as detailed in [1] on a preliminary SNR-2 geometry, the predicted top displacements exceeded the design requirements for control rod insertion and the reactivity changes due to the horizontal motion were surprisingly high.

These conclusions were known to be pessimistic, especially for the reactivity which depends on relative displacements, but nobody knew how much.

This paper attempts to clarify the role of the fluid and to quantify its effect on the core response.

2. ADDED MASS MATRIX

As a preliminary, we investigated the fluid-coupling in an array of hexagonal prisms [2]. A plane finite element programme was developed, assuming an incompressible, non-viscous fluid. Advantage was taken of the fact that, within the core, the pressure was almost constant across the thickness of the (inter-assembly) gap, and therefore, the flow in the narrow space between the subassemblies could be modelled by one-dimensional elements with parabolic pressure field (3 nodes per element). This led to an enormous savings in the discretization.

In parallel to that, an experiment was set up and fluid-coupling coefficients were actually identified. Experimental values were consistent with the numerical results, although 20 to 25 % smaller, due to axial leaks in the tests.

3. CORE MODELLING

3-D calculations have demonstrated that, under seismic excitations, the overall response of the subassemblies is dominated by the first mode contribution. This suggests to use a model like that of Fig. 1 to evaluate the fluid-coupling effects. In this model, each subassembly (or rather macro-assembly, as we shall see later) is represented by simple oscillators along the x and y axes. Impacts are represented by classical impact elements, as before. The fluid-coupling is taken into account by the full added mass matrix, determined as explained in the foregoing section. The equation of motion reads [2]

$$(M + \alpha F)\ddot{\underline{y}} + (C + C_f)\dot{\underline{y}} + K\,\underline{y} = f(\underline{y},\dot{\underline{y}},\underline{g}) - \left\{(M + \alpha F)T_{qs} + \alpha F_{10}\right\}\ddot{\underline{x}}_o \qquad (1)$$

where $\underline{y}$ stands for the displacements relative to the grid plate, $M = \mathrm{diag}(m_i)$, $K = \mathrm{diag}(k_i)$, $C = \mathrm{diag}(C_i)$ are the structural mass, stiffness and damping matrices and F and F_{10} are the hydrodynamic mass matrices [2] (the subcript o refers to the container). T_{qs} is the quasi-static transmission matrix, relating the absolute displacements to those of the supports. $\underline{f}$ is the non-linear term resulting from impacts, function of $\underline{y},\dot{\underline{y}}$ and the gap distribution $\underline{g}$. α is a parameter that we have introduced to account for axial leaks and to allow a parametric study of the fluid effect ($\alpha = 0$ corresponds to no fluid).

A programme named FLASH has been developed to integrate (1), using the same concepts as in CLASH [1]. The input data are discussed next.

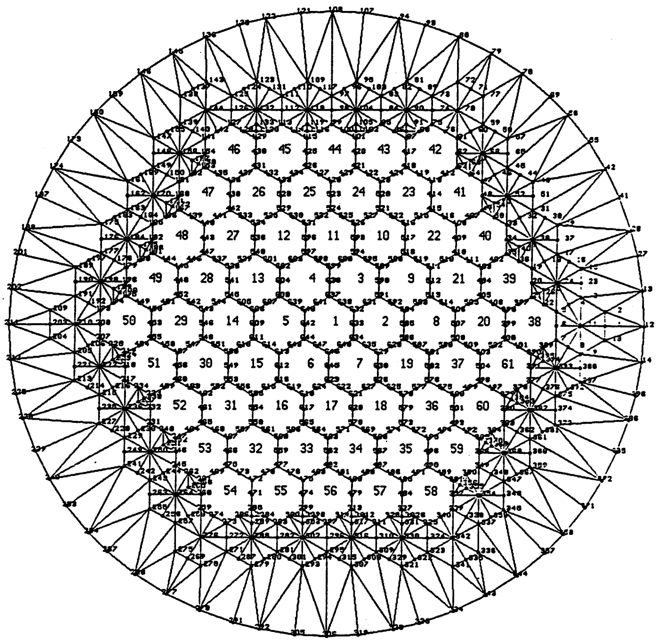

FIG. 1 - Model

4. LUMPING PROCEDURE FOR MACRO-ASSEMBLIES

Right from the start, it was apparent that it would not be sensible to model every single subassembly of a large core (more than 1000). Instead, it would be preferable to lump them into macro-assemblies. The question arised, then, of how to choose the properties for the lumped subassemblies, particularly for those macro-assemblies involving several types of subassemblies. The principle we have adopted is as follows :

- Add the mass, add the stiffness (and thus keep the natural frequency the same), add the neutronic influence coefficients within a macro-assembly.
- Regarding the impact elements, we have added the gaps radially, added the damping coefficients and kept the stiffness of a single impact element. (This latter rule is dictated by the fact that the subassemblies combine both in parallel and in series within a macro).

The assumptions on the damping and stiffness of the impact elements may look a bit reckless, but we know from previous parameter studies that the core response is not too sensitive to these parameters.

5. EXTRAPOLATION RULE

The next question is how to extrapolate the results obtained with single degree of freedom oscillators to various levels in the core : maximum displacement at the top for control rod insertion and at mid-core for reactivity calculations. To do that, it has been assumed that each subassembly responds according to mode 1. Consequently, the modal amplitude follows

$$\ddot{z} + 2\,\xi\omega\dot{z} + \omega^2 z = \frac{-\int m\varphi\,dx}{\int m\varphi^2\,dx}\,\ddot{x}_o = -\frac{\Gamma}{\mu}\,\ddot{x}_o \tag{2}$$

where φ stands for the first mode shape of an actual assembly and Γ is the modal participation factor. It follows that the 2-D results y can be converted into 3-D information according to

$$x(\text{top}) = \varphi(\text{top})\ z = \Gamma/\mu\ .\ \varphi(\text{top})\ .\ y \tag{3}$$

$$x(\text{mid-core}) = \Gamma/\mu\ .\ \varphi(\text{mid-core})\ .\ y \tag{4}$$

6. COMPARISON CLASH - FLASH

Some of the assumptions leading to equivalent input data for the 2-D model are a little daring and it seems appropriate, before investigating the effect of the fluid, to compare the results of the structural model only ($\alpha = 0$) with those of the full 3-D model. This has been done for the SNR-2 case documented in [1]. The 2-D model involves 61 macro-assemblies. Various geometries have been analysed, with different numbers of neutron shield elements. Note that an interesting feature of our lumping procedure is that it allows for incomplete rows. If, for example, neutron shield elements are removed from the outer row, it is reflected by decreased mass and stiffness of the outer row of the FLASH model.

Trajectories of the top displacements of the approximate model are very close to those obtained with the 3-D model. The reactivity curves are also very close, both in shape and in amplitude (the comparison is not shown due to the lack of space, but Fig. 8 of [1] can be compared to Fig. 2a). Equally good results have been obtained when stiffer outer rows are added (compare Fig. 2b - with Fig. 11 of [1]). A good agreement is also obtained for the maximum top displacements as reported in Table I.

Table I

CLASH-FLASH COMPARISON - TOP DISPLACEMENTS (cm)

Core configuration	FLASH	CLASH [1]
817 (baseline)	14.9	12.2
1027 (+ 2 rims PNL)	19.6	21

7. INFLUENCE OF THE FLUID

Now that we have shown that the lumping procedure leads to results in good agreement with 3-D calculations, the next step is to investigate the effect of the fluid-coupling. This is done by varying the coefficient α in equation (1) between 0 and 1 ($\alpha = 0$ corresponds to no fluid and $\alpha = 1$ accounts for the full added mass matrix obtained from 2-D calculations, with a representative geometry). We expect that the actual value of α must lie somewhere between 0 and 1, because of axial leaks. The effect of α on the reactivity variation is analysed in Fig. 2 for two core configurations. These figures demonstrate that the fluid-coupling leads to a substantial reduction of the reactivity variation induced by the core compaction, as expected.

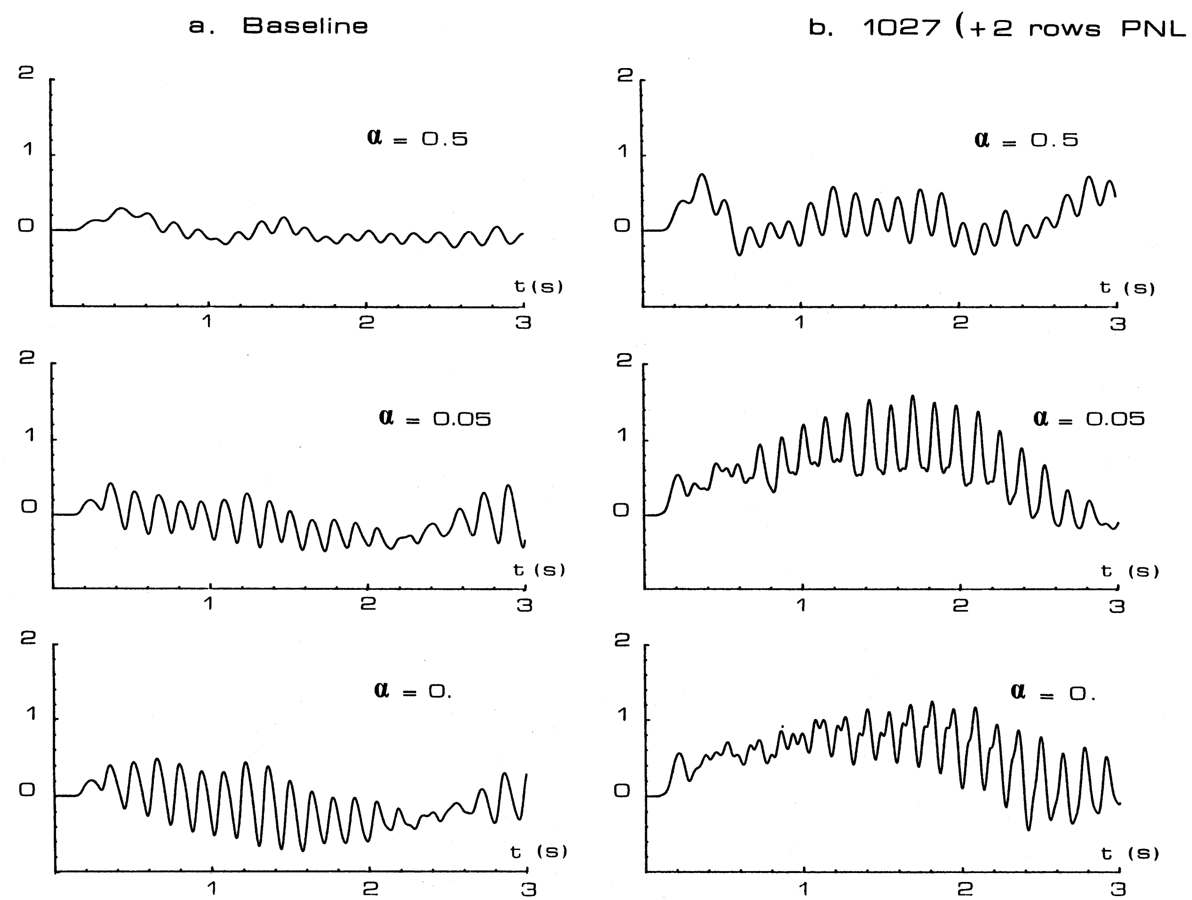

FIG. 2 - Effect of α on reactivity ($\Delta\rho/\rho \times 10^3$)

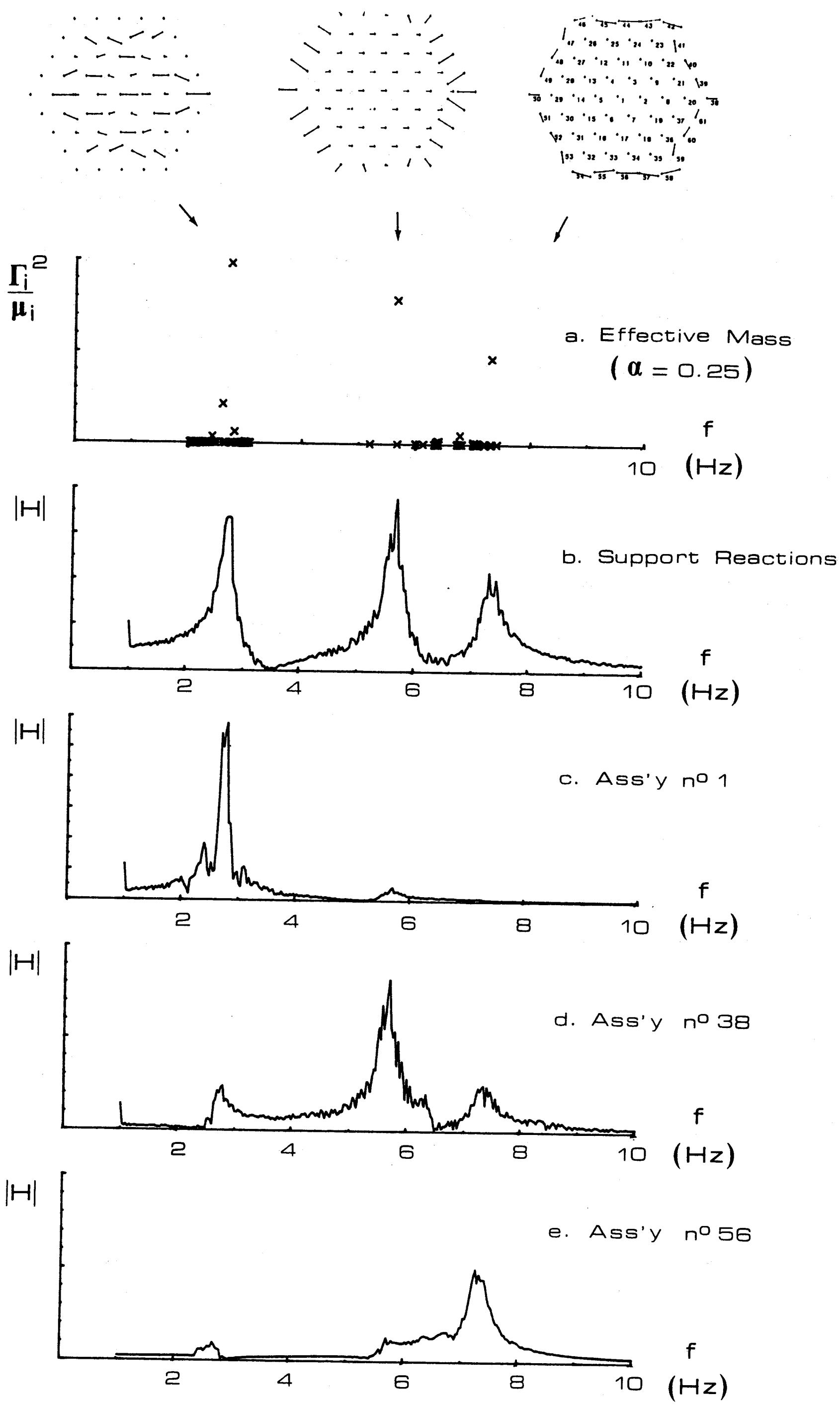

FIG. 3 - Transfer functions between various response quantities and the core plate excitation (simulations).

8. IDENTIFICATION OF α

Once the fluid coupling is included in equation (1), instead of having a discrete set of natural frequencies, corresponding to uncoupled modes of each type of subassemblies, one gets a cluster of closely spaced modes (typically, 100 modes within a few Hertz). Not all of them are excited by the seismic excitation as can be seen from the effective mass plot for an excitation along Ox (Fig. 3a). This plot (for $\alpha = 0.25$) reveals that only a limited number of modes are significantly excited and they can be used to identify the right value of α from shaking table experiments. In this case, there are only 3 modes which are significantly excited. Their mode shapes are illustrated on top of Fig. 3. The evolution of the corresponding natural frequencies with α is shown in Fig. 4.

Clues as to the way α can be determined from shaking table experiments are given in Figs. 3b to 3e, where various transfer functions between support reactions and subassemblies top displacements are drawn. These transfer functions have been obtained by simulation, using a white noise excitation with maximum acceleration 0.1 m/s^2.

9. REFERENCES

[1] A. PREUMONT et al. (1987).
The Seismic Analysis of a Free Standing FBR Core.
Nuclear Engineering and Design 103, 199-210.

[2] A. PREUMONT et al. (1986).
Fluid-Coupling Coefficients in an Array of Hexagonal Prisms.
Nuclear Engineering and Design 92, 51-59

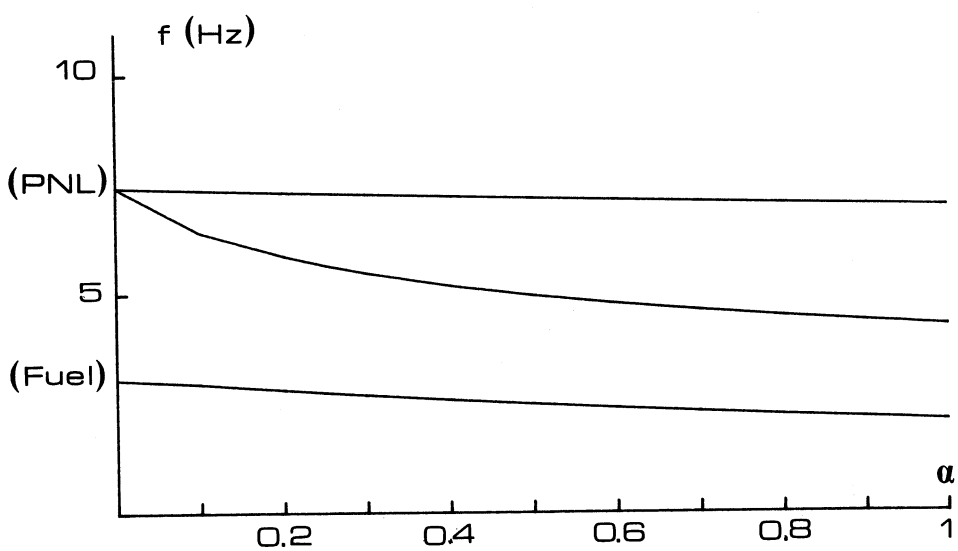

FIG. 4 - Effect of α on the natural frequencies