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FLUID STRUCTURE INTERACTION IN THE RESPONSE OF PWR FUEL ASSEMBLIES TO HORIZONTAL SEISMIC LOADS

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1. INTRODUCTION

In the PWR fuel assembly row models currently used for justification of Fuel Assembly (F/A) lateral strength during an earthquake, non-damping effects of primary coolant are reduced to a single added mass for each F/A, which is obtained from in-air and in-water frequency measurements /1/. The aim of this paper is to present a fluid interaction model which allows for actual coupling between core structures, i.e. F/A's and core baffles. It is recalled that a single horizontal direction of motion is considered, along the F/A row model.

2.BASIC ASSUMPTIONS AND FEATURES FOR IN-CORE HYDRAULIC COUPLING

2.1.General equations and coupling effect

By assuming small motion amplitudes in an incompressible and non-viscous fluid, continuity and momentum transfer equations are linearized :

$$\operatorname{div} \vec{V} = 0 \qquad (1) \qquad\qquad \overrightarrow{\operatorname{grad}}\, P = -\rho \frac{\partial \vec{V}}{\partial t} \qquad (2)$$

where V, P and ρ stand for fluid velocity, pressure and density respectively. Therefore the pressure field is a solution of Laplace equation :

$$\Delta P = 0 \qquad (3)$$

with boundary conditions corresponding to the structural acceleration component perpendicular to the solid surface (through eq. (2)). Coupling then results from the reciprocal action of pressure loads on structural motions, and for discrete models, the linear force-acceleration relationship leads to the well known added mass matrix concept.

2.2. Reduction to coupling between rigid cross-sections

Since F/A's are very tall vertical structures modelled by beam elements, it may be assumed that their horizontal cross-section, i.e. the fuel rod array, remains perfectly rigid (as core baffles). Then coupling is similar to that between solids described by FRITZ /2/, each added mass matrix term m_{ij} being defined by the pressure force ($-m_{ij}$) on solid S_i resulting from unit acceleration of solid S_j, or vice-versa. Such a plane coupling yields values per unit height, and in the structural model, coupling is considered only between nodes at the same vertical level, with values proportional to the modelled height (similarly to structural mass).

Finite element solutions of eq. (3) and pressure force integration can be obtained by adapting standard formulations. Both fluid-shell interaction with very stiff shells at solid outlines (CASTEM 2000), and thermal analogy with specific interface conditions (SYSTUS) have been used, and yield similar results.

2.3. Consistency relationships

Consider a set of (n - 1) immersed solids S_i (F/A's), S_n corresponding to the baffles, and a rigid-body acceleration γ of such a system. Then fluid acceleration and pressure gradient are uniform, and eq. (2) is very similar to that of hydrostatics ; this implies that the resulting force on S_i is equal to $(m_{di}\ \gamma)$, where m_{di} stands for the displaced fluid mass used in buoyancy force $(m_{di}\ g)$, and therefore the consistency relationships for coupling terms :

$$\sum_{j=1}^{n} m_{ij} = - m_{di} \qquad i = 1 \text{ to } (n - 1) \tag{4}$$

From eq. (4) and a similar one for S_n, the total sum of m_{ij}'s is equal to the fluid mass, yet this mass merely represents the fluid inertia, although the displaced masses m_{di} are typical of a fluid problem. Moreover, when considering a non-rigid but forced (or quasi-static) structural response, it can be easily shown that the response of S_i is proportional to the loading force :

$$f_i(t) = - (m_i - m_{di})\ \gamma(t) \qquad i = 1 \text{ to } (n - 1) \tag{5}$$

where m_i stands for the solid mass, and thus coupling leads to a decrease in loading inertia forces for immersed structures, instead of a fictitious increase when allowing for a single added mass (m_{ii}) only. This physical interpretation of consistency relationships (4) in a particular but realistic case clearly calls for their fulfillment in coupling models.

3. COUPLING TERM DETERMINATION

3.1. Specific assumptions and fluid models

Let X be the motion direction, Y the perpendicular direction. If it is assumed that all the F/A rows parallel to X have the same motion, and that gaps between such rows are negligible, geometrical and mechanical periodicity are achieved in Y direction ; and as the fuel rod (f/r) rows parallel to X may then be considered as separated by solid walls, located at the f/r cell boundaries, the Y-periodicity is not broken by the baffle plates parallel to X. Then the fluid models may be reduced to a small number of f/r rows parallel to X, or even to a single one if no lateral gap is included. In direction X, i.e. in the F/A row, a small number of F/A's is considered, each comprising a small number of f/r's, yet always sufficient to allow for edge or internal positions of assemblies and rods.

Two typical models are presented herein. The first one, on figure 1, is designed for a single row of 6 x 6 f/r array mock-ups, used in shaker table tests /3/ /4/ : then a complete 3-mock-up row is represented with a lateral gap (and 3 f/r rows only because of symmetry). On the contrary, the model which displays the motion fields on fig. 2 corresponds to the maximum reduction compatible with the previous modelling principles (half f/r row due to symmetry). In all the models, the rod diameter is 9.5 mm, with a 12.6 mm pitch, identical to those of 17 x 17 F/A's ; when included, gaps between assemblies or with baffles are always about 1 mm.

3.2. Results and coupling features

The results obtained display the following features of coupling :

- Coupling is negligible between F/A's : it is found for edge position f/r's only, and represents roughly 1 % of f/r contributions to other terms.
- Coupling is almost uniform, i.e. independent of F/A position, with f/r contributions independent of f/r positions : differences in f/r contributions are less than 2 %, and than 1 % when excluding positions next to baffles.

Therefore coupling is characterized by a single value of added mass m_a, and of negative coupling term with baffles m_c, for any F/A position ; the almost uniform f/r contribution allows easy extrapolations, i.e. for the 17 x 17 F/A's. The numerical values are presented in the table below, in dimensionless form :

F/A COUPLING TERMS	RATIO TO SOLID MASS		RATIO TO FLUID DISPLACED MASS m_d	
	6 x 6 mock-up row model, cold	17 x 17 F/A, extrapolation, PWR cond.	6 x 6 mock-up row model	extrapolations from f/r single row
Added mass m_a	0.290	0.253	2.364	2.675
Baffle coupling m_c	- 0.411	- 0.348	- 3.341	- 3.674
$\|m_c\| - m_a \simeq m_d$	0.121	0.095	0.977	0.999

These values are relatively large, reflecting the in-core confinement : m_a/m_d is much closer to 1 when derived from in-pool frequency tests, and in an infinite medium, the above value of m_a would represent that of a F/A cross section solid beam /2/. For the ratio to m_d, temperature and assembly size independent, the differences are related to the lateral gap in the mock-up row model.

Finally, for any F/A, the consistency relationships (4) are reduced to :

$$m_a + m_c = - m_d \qquad (6)$$

which calls for the following key remarks. Although there is no structural modelling of the baffles (they are merely used as stops), they play an essential part in fluid coupling consistency. Furthermore, as their motion is identical (or very close) to the seismic input motion with acceleration $\gamma(t)$, eq. (5) is applicable to the equivalent loading forces in F/A relative motion, i.e. reduced inertia forces, even for a truly dynamic F/A response.

3.3. Interpretation from the fluid acceleration and pressure gradient fields

Acceleration, to which pressure gradient is proportional, is the only motion field to be significant in hydraulic coupling. As eq. (1) holds for fluid acceleration, its flux is conserved in the fluid, with sources on accelerated solid outlines only.

When accelerating a F/A (figures 2.A and B), the field cannot spread outside this F/A, where there are no flux sources, which leads to very weak or zero pressure gradient in other F/A's : then coupling is negligible with these F/A's, but the pressure difference generated between the accelerated F/A ends is completely transferred to the baffles through the zero-gradient regions, wherever the F/A may be. As most of the f/r generated flux is transferred from one f/r side to the other, there results approximate independence of f/r cell behaviour and thus similar f/r contributions. The uniform character of coupling with baffles is still more obvious when considering baffle acceleration (figure 2.C), since the field appears to be periodic in the complete row, just because the fluxes at cell boundaries are identical to that generated on baffles. This feature is confirmed by the mean pressure linear variation along the 3-mock-up row model, as displayed on fig.3.

Approximate independence of f/r cells for coupling effects is confirmed by using a single f/r model, with baffles at cell boundaries, which yields coupling terms larger by less than 10 % than those from the f/r single row model. It is noteworthy that this property is obtained for a relatively small pitch ratio, therefore a dense array, since it is obvious only for tiny rods in wide cells, with much smaller coupling terms (m_a/m_d = 1 and m_c/m_d = - 2 for cylinders in a large plenum). This also provides a justification for the homogeneization methods described in ref. /5/.

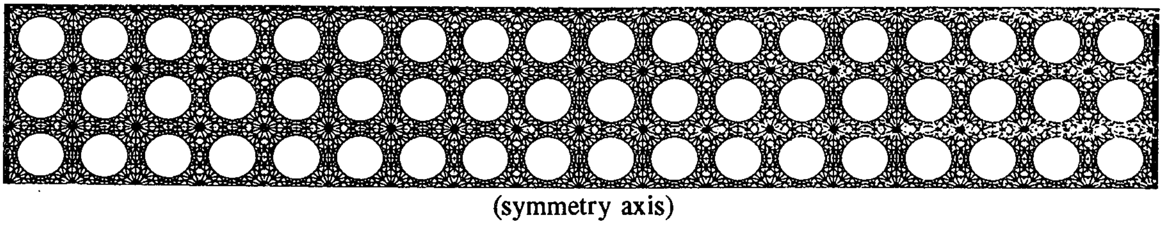
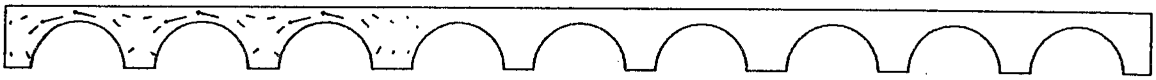


FIGURE 1 : FLUID MODEL FOR A ROW OF THREE 6 X 6 MOCK-UPS



A : For left assembly acceleration

B : For central assembly acceleration

C : For baffle acceleration

FIGURE 2 : FLUID ACCELERATIONS IN A FUEL ROD SINGLE ROW MODEL (3 ASSEMBLIES, EACH COMPRISING 3 FUEL RODS)

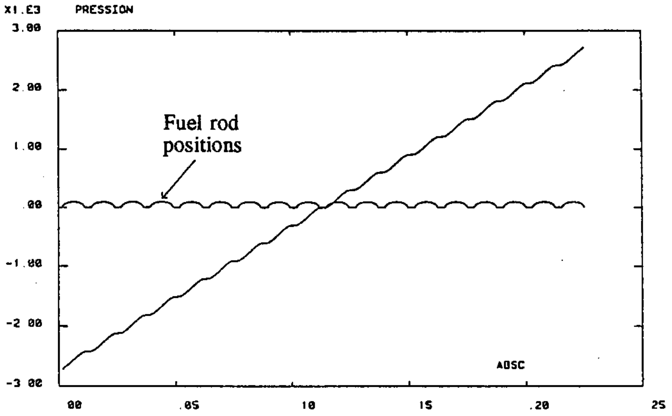


FIGURE 3 : PRESSURE VARIATION ALONG THE 3-MOCK-UP-ROW (FOR BAFFLE ACCELERATION)

3.4. Discussion on model validity

The previous consideration validity is obviously dependent upon the lateral confinement of all the core f/r rows, and thus upon the absence of F/A row differential motions. Yet the coupling between rows resulting from differential motion cannot be allowed for in the current F/A single row seismic model, whose lateral confinement seems to be the most acceptable hypothesis. Furthermore, coupling terms with baffles are not dependent upon this differential motion, since they represent pressure forces on immobile F/A's when accelerating baffles. Larger fluid models with F/A row differential motions are under way, but the first estimates show that coupling between F/A's and change in added mass are likely to be moderate. Moreover, in shaker table tests, the behaviour of the "core-mock-up" pattern is found similar to that of a single and laterally confined row /4/ /6/.

4. COUPLING MODEL APPLICATIONS

Applications to industrial models are presented in ref. /6/, where the coupling model is found more consistent with test results than the single added mass one. A more detailed comparison with shaker table tests on rows of 5 or 13 (6 x 6) mock-ups is presented hereafter, using a more refined structural model developed by CEA for a test interpretation purpose.

The model is similar to that of ref. /3/, for in-air calculations, but with the added mass m_a to the beams representing the assemblies, and introducing the coupling term with baffles $[-m_c \, \gamma(t)]$ at the right hand side of motion equation (loading forces), since the solution provides the assembly relative motion through the non-linear modal combination method. Damping is the same for the 5 modes which are allowed for, i.e. 15 % of critical damping for the 5-mock-up row, and 19% for the 13-mock-up row (due to larger motion amplitude). The gap values between assemblies and with the uprights simulating core baffles are real ones, derived from tests. Numerical results are given by the table below, displacement and impact force vs. time curves are displayed on fig. 4 and 5 (13-mock-up row response).

SEISMIC RESPONSE PARAMETERS	5-mock-up row		13-mock-up row	
	Test	Model	Test	Model
Maximum Impact Force (N)	979	1160	1733	2084
Impact Force Integral (N.s)	1436	1859	2595	3555
Total Impact Duration (s)	14.66	20.10	16.72	19.83

A good agreement between test and calculations is found for the displacement and force time histories. The model yields impacts occurring at the same instants as in test, and the same number of significant force peaks (larger than 100 N). On the contrary, the maximum impact force, the force integral and the impact total duration are overestimated by the model. This is mainly related to the spring-mass type impact model, which cannot provide a refined description of impacts in fluid, yet which is satisfactory for reflecting the overall effect of impacts in core response. It should finally be noted that the ratio of the 13-mock-up results to the 5-mock-up ones are roughly equal to the number ratio 13/5, which is mainly due to the increase in the total gap in the row and therefore in motion amplitude.

5. CONCLUSIONS

Allowance for coupling between core structures is desirable for physical consistency, and it leads to a decrease in F/A loading forces. Coupling term determination can be performed from small models by neglecting differential motions between F/A rows parallel to motion direction, which is consistent with the single row seismic model, and also found little restrictive. Coupling is then defined by the F/A added mass and coupling term with core baffles, independent of F/A position, coupling between assemblies being negligible. When applied to seismic response, this coupling model is found consistent with results from shaker table tests on interacting F/A mock-ups.

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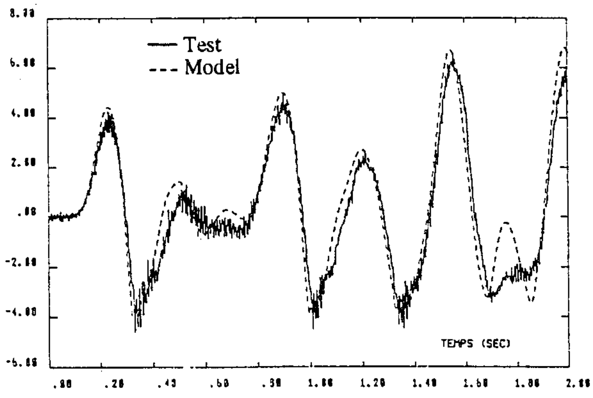

FIGURE 4 : ROW END MOCK-UP DISPLACEMENT VS. TIME

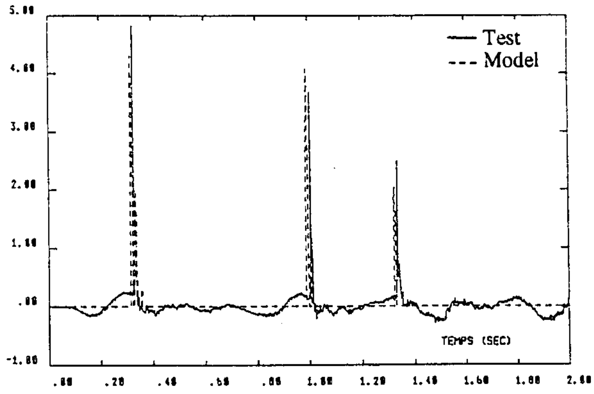

FIGURE 5 : IMPACT FORCE AT ROW END VS. TIME