Vessel-Core Seismic Interaction for a Fast Reactor

A. Martelli, S. Chiocchio
ENEA, Dipartimento Reattori Veloci, Via dell'Arcoveggio 56/23, I-40129 Bologna, Italy
G. Maresca
NIRA S.p.A., Via Dei Pescatori 35, I-16100 Genova, Italy

Summary

The numerical analysis for the seismic verification of the PEC Fast Reactor Test Facility is carried out in collaboration between the Department of Fast Reactors (DRV) of ENEA and NIRA. More precisely, the studies of ENEA-DRV concern only the core, while those of NIRA deal with the remaining parts of the reactor.

As regards the core, the non-linear computer program CORALIE is used: this code, developed in collaboration between ENEA and CEA, allows taking into account the strong effects of the shocks occurring among the core elements in the case of a severe horizontal excitation and those of the fluid.

The code obviously requires as input data, beside the vibrational behaviour of the different element types and the shock and fluid-structure interaction parameters, also the time-histories of the seismic motion at the vessel-core interfaces (core support grid, and eventually core restraint plates), which are evaluated by means of linear calculations carried out by NIRA on the whole reactor.

However, at least in the PEC case, the above mentioned core boundary conditions depend strongly on the linear core schematization assumed in the NIRA analysis.

For this reason, we apply an iterative procedure between NIRA and ENEA calculations, which was assessed improving a method suggested by CEA and used for the Superphenix - 1 core seismic verification.

The procedure was tested both referring to the original unrestrained PEC core design and to the case of single and double restraint.

The paper describes the fundamentals of the procedure, devoting special attention to the linearization method of the CORALIE response (which represents the main improvement of the method suggested by CEA) and presents the results obtained for the various core models.

1. Introduction

A considerable effort is devoted by the Department of Fast Reactors(DRV) of the Italian National Commitee for the Research and the Development of the Nuclear and the Renewable Energies (ENEA) to the seismic verification of the PEC Fast Reactor Test Facility /1/.

According to the safety and the economic requirements concerning a LMFBR, it is necessary to demonstrate that the control rods can fall inside the corresponding guide-tubes (located within the core) and the core elements do not fail up to the "Safe Shut-down Earthquake" (SSE), and furthermore, that the integrity of such elements is kept up to the "Operational Basis Earthquake" (OBE) /2/.

To prove that such design requirements are satisfied, the computer program CORALIE was developed in co-operation between ENEA-DRV and the Departement of the Mechanical and Thermal Studies of the French Atomic Energy Agency (CEA-DEMT), which allows the calculation of the core seismic response, taking into account the effects of the shocks occurring among core elements and those of the fluid-structure interaction /1,3,4,5/. Furthermore, experimental tests were organized by ENEA-DRV for assessing the vibrational and dynamic behaviour of the PEC core elements and by the Company NIRA for testing the capabilities of the Control-Rod Drive Mechanism /6,7,8/. Finally, a linearization model of the core non-linear response calculated with CORALIE was recently developed, improving a method proposed by CEA /9/.

This paper deals only with the fundamentals of this last procedure and with applications to various PEC core configurations, namely the original unrestrained one and that with one or two restraints (located close to the core middle and top planes, see fig. 1), whose effects were studied in order to improve the core seismic behaviour /10/.

No description of the code CORALIE is contained, because its main features have been already presented in the mentioned references. Finally, our most recent experimental results and those of a study on the effects of the input uncertainties are presented at this Conference in two separate papers/8,11/.

2. The iterative procedure

The necessity of linearizing the core dynamic response is due to the fact that the seismic calculations of the whole Reactor Block (fig. 1) are performed with linear methods (i.e. not modeling shocks nor including coupuling due to fluid-structure interaction): to do this, it is obviously necessary to make use of a linear model for the core, also. However, as we will show below, the vessel-core dynamic interaction is very strong in the PEC case:thus the dynamic response calculated with CORALIE for the core(and that of other components also) depends strongly on the core model assumed in the linear calculations of the whole Reactor Block /10,12/. This implies the necessity of an interative procedure between the linear calculations of the whole Reactor Block and the non-linear ones of the single core, as shown by fig. 2.

First of all, the acceleration time-histories at the ground are evaluated by NIRA from the Desing Spectra, according to the U.S. Codes. The dynamic analysis of reactor building provides the boundary conditions (seismic motion at the vessel support structure floor, see fig. 1) for the Reactor Block, which are assumed not to be affected by the core non-linear behaviour.

The calculations of the Reactor Block are performed by NIRA with the program SAP IV /13/, applying a lumped-mass model: more precisely, the modal shapes are evaluated with SAP IV, then they are recombined with a code developed by NIRA, taking into account the different values of the fractions of critical damping of the various concerned structures.

In the first step of the Reactor Block calculations it is necessary to assume a rather rough linear core model due to the lack of information on the real core behaviour (see Par. 4). By means of these calculations the seismic motion at the core interfaces is obtained, which allows to perform the core analysis with CORALIE. On the basis of the core dynamic response a linear core model is defined (see Par. 3): this is applied for repeating the Reactor Block calculations, which provide new boundary conditions for the core analysis. Then, the non-linear CORALIE runs are carried out again, and conseguently, a new linear core model is defined.

The iterative procedure is repeated until convergence is reached, namely until values of the core response are obtained, which are approximatively equal to the corresponding ones evaluated in the preceding interation.

3. The equivalent linear core model

The equivalent linear core model must be such as to apply loads on the reactor vessel, whose values are as close as possibile to those calculated in the non-linear analysis.

In the case of an unrestrained core, such as that of the French Superphenix-1 Fast Reactor or the PEC original one, this means that the transfer functions T(f) between the core support grid acceleration, a(t), and the core total reaction force and moment, R(t), corresponding to the linear model(1)

$$T(f) = \mathcal{F}[R(t)] \quad / \quad \mathcal{F}[a(t)] \tag{1}$$

must provide the best possible approximation of those obtained from the results of the CORALIE analysis: in fact, in the case of a really linear system, T(f) is invariant with respect to the excitation shape /1/. Moreover, it is important to note that, at least in the PEC case, the acceleration time-histories at the locations of the core restraint plates are practically equal to that of the support grid /14/: this allows to make use of eq. (1)for the restrained PEC core models also, including in R(t) the loads acting on the restraint plates.

For the definition of the equivalent linear core model we assumed a system of independent oscillators and we judged to be correct enough to approximate only the amplitudes of the transfer functions, $|T(f)|$ /1,14/.

First of all, to obtain this model, it is necessary to extrapolate the results computed with CORALIE to the whole core: in fact, the CORALIE runs are normally performed for a single row of core elements, in order to limit the computer time to acceptable values /1,3,4,5,10,14/. For the present study, whose aim was only to verify the reliability of the proposed iterative procedure and the applicability of the core response linearization method,we carried out the CORALIE computations only for the central row of PEC core elements, assuming that the total reaction force and moment, R(t), acting on the vessel,are given by the equation

$$R(t) = \sum_{K=1}^{n_T} \left\{ \left[\sum_{i=1}^{n_{KF}} R_{iK}(t) \right] \cdot \frac{n_{KN}}{n_{KF}} \right\} + \sum_{j=1}^{n_P} Q_j(t) n_F , \tag{2}$$

in which $R_{iK}(t)$ are the time-histories of the corresponding total reaction loads on the support grid due to all elements of type "K" of the row analysed with CORALIE, $Q_j(t)$those due to the shocks of the core external elements against the n_P restraint plates (assumed to be rigidly connected to the core support grid),n_T is the number of different element types present in the

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(1) We indicate with $\mathcal{F}$ the Fourier Transform and with f the frequency.

core, n_F that of the element rows, and finally, n_{KF} and n_{KN} the numbers of elements of type K in the analysed row and in the core, respectively.

The use of eq. (2) means practically to assume that the mean motion of the elements of the same type is equal in all different core element rows (a more correct approach will be applied, if necessary, in the final verification analysis, combining properly the results of CORALIE runs performed for different core elements rows).

After obtaining the time-histories of the reaction loads by means of eq. (2), the values of $|T(f)|$ are computed according to eq.(1), using the computer code TIROIR /15/.

Finally, the number n_o of the oscillators of the equivalent linear core model, the values of the frequencies f_i, the fractions of critical damping η_i, the masses m_i and the distances h_i of these oscillators from the core support grid are evaluated with the program OSCILLO developed at ENEA-DRV/14/, approximating (1) with the equation:

$$|T(f)| \cong \left[\left[\sum_{i=1}^{n_o} \frac{m_i \left[1 - (f/f_i)^2\right] x_i}{\left[1-(f/f_i)^2\right]^2 + 4\eta_i^2 (f/f_i)^2} \right]^2 + 4 \left[\sum_{i=1}^{n_o} \frac{\eta_i \, m_i \, (f/f_i) \quad x_i}{\left[1-(f/f_i)^2\right]^2 + 4\eta_i^2 (f/f_i)^2} \right]^2 \right]^{\frac{1}{2}} \qquad (3)$$

which can be easily obtained for a system of independent oscillators ($x_i=1$ for the reaction force equation and $x_i=h_i$ for that of the reaction moment).

4. Application of the iterative procedure

The applicability of the iterative procedure and the linearization model previously described was proved by means of calculations carried out on the basis of preliminary data concerning the vibrational behaviour of the PEC core elements (i.e. not corrected, yet, to take into account the results of our experimental tests) and neglecting the fluid-structure interaction effects /1,14/.

The first study concerned the original unrestrained core design. For this, the calculations were started from two different first iteration linear core models: in the first one we assumed that the core elements are completely free to move, as if the values of the gaps among them were very large; in the second one, on the contrary, we supposed that these elements are hinged to one another at the pads located in the middle core plane (fig. 3).

The top level maximum displacement values computed with CORALIE on the basis of the acceleration time-histories corresponding to these two models are presented in tab. I for the first three iterations of the reactor block-core calculations. This table shows that, in the first series of runs convergence is practically reached at the third iteration. Furthermore, the differences in the results of the two calculation series are very small at the third iteration: this indicates that convergence would be reached in the next iteration, for the second series of runs also, and furthermore, demonstrates that our iterative procedure is correct (the final results have obviously to be the same, independently of the first iteration linear core model). It is also interesting to note that the first iteration results are very conservative with respect to the final ones, which stresses the importance of the tank-core seismic interaction effect in the PEC case.

Due to the good results obtained for the unrestrained core design, our study was carried on for two other core configurations, namely that with a restraint structure located near the middle core plane and that with a second restraint close to the top plane. Also for these the first iteration runs were performed assuming two different linear core models: in the first one we assumed that the elements are hinged to one another at the pads located in the middle core plane, but free to move on the side of the restraint plates, as if no shocks could occur against them; in the second one, on the contrary, we supposed that these elements are hinged to one another and to the support grid at the axial locations of the restraint plates, also (fig.3). The results of the first iteration calculations are shown in tabs.II and III. the large effect of the tank-core seismic interaction is again evident.

As regards the iteration, this was performed only starting from the second above cited linear core model, in order to limit the computation time: this, in fact, provides the highest first iteration response values, as for the first model in the case of the unrestrained core configuration, for which the convergence was the fastest.

The top level maximum displacement values computed with CORALIE at the various iterations are also presented in tabs.II and III These tables show that convergence, although slower, is reached for the restrained core configurations also, and that the tank-core seismic interaction effect is even stronger than in the case of the unrestrained core design.

Finally, we show in fig. 4, as an example, the reaction force transfer function amplitudes at the various iterations for the core configuration with a single restraint in its middle plane, and in fig. 5 a comparison between the results of the TIROIR and the OSCILLO calculations(for other esamples see ref. /1/).

5. Conclusions

We have shown that the iterative procedure between the reactor block and the core calculations used for the PEC seismic verification converges well, both in the case of unrestrained and restrained core, although the tank-core dynamic interaction is quite strong.

Due to this result ,the procedure is now applied for the actual PEC core seismic verification, which accounts for the experimental results obtained in the meantime.

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Tab. I : Effects of the iterative procedure on the core element displacement values in the case of unrestrained core

ELEMENT TYPE	MAXIMUM TOP LEVEL DISPLACEMENTS (mm)					
	1st iterat.		2nd iterat.		3rd iterat.	
	mod.1	mod.2	mod.1	mod.2	mod.1	mod.2
Central fuel	32	24	20	20	19	18
Forced fuel	37	31	19	25	20	20
Normal refl.	54	44	30	37	32	30
Neutron shield	48	34	22	25	22	22
Fuel at decay	42	36	20	29	21	20

Tab. III : Effects of the iterative procedure on the core element displacement values in the case of double core restraint

ELEMENT TYPE	MAXIMUM TOP LEVEL DISPLACEMENTS (mm)						
	iterat. 1		it.2	it.3	it.4	it.5	it.6
	mod.1	mod.2	model 2				
Central fuel	26	31	33	25	26	18	17
Forced fuel	31	34	39	32	32	22	21
Normal refl.	32	37	41	33	33	24	23
Neutron shield	26	30	30	27	26	17	17
Fuel at decay	17	25	26	23	21	16	16

Tab. II : Effects of the iterative procedure on the core element displacement values in the case of a single restraint in the core middle plane

ELEMENT TYPE	MAX. TOP LEVEL DISPLAC. (mm)				
	iterat. 1		it. 2	it. 3	it. 4
	mod.1	mod.2	model 2		
Central fuel	36	61	21	20	20
Forced fuel	38	70	31	20	20
Normal refl.	46	77	40	30	28
Neutron shield	35	55	28	23	23
Fuel at decay	28	60	25	20	20

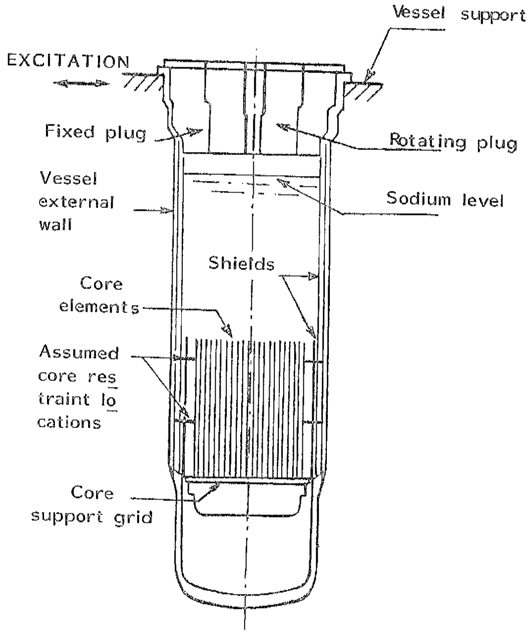

Fig 1 : Sketch of the PEC reactor vessel and core

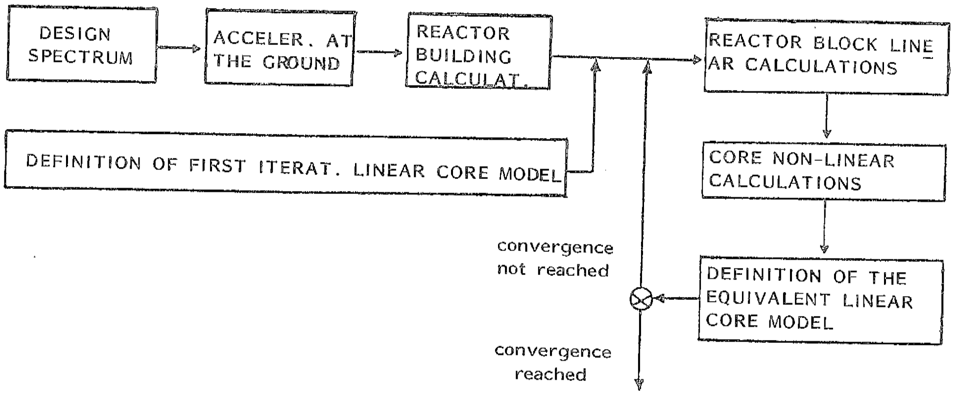

Fig 2 : Flow-chart of the iterative procedure adopted to account for the vessel-core dynamic interaction

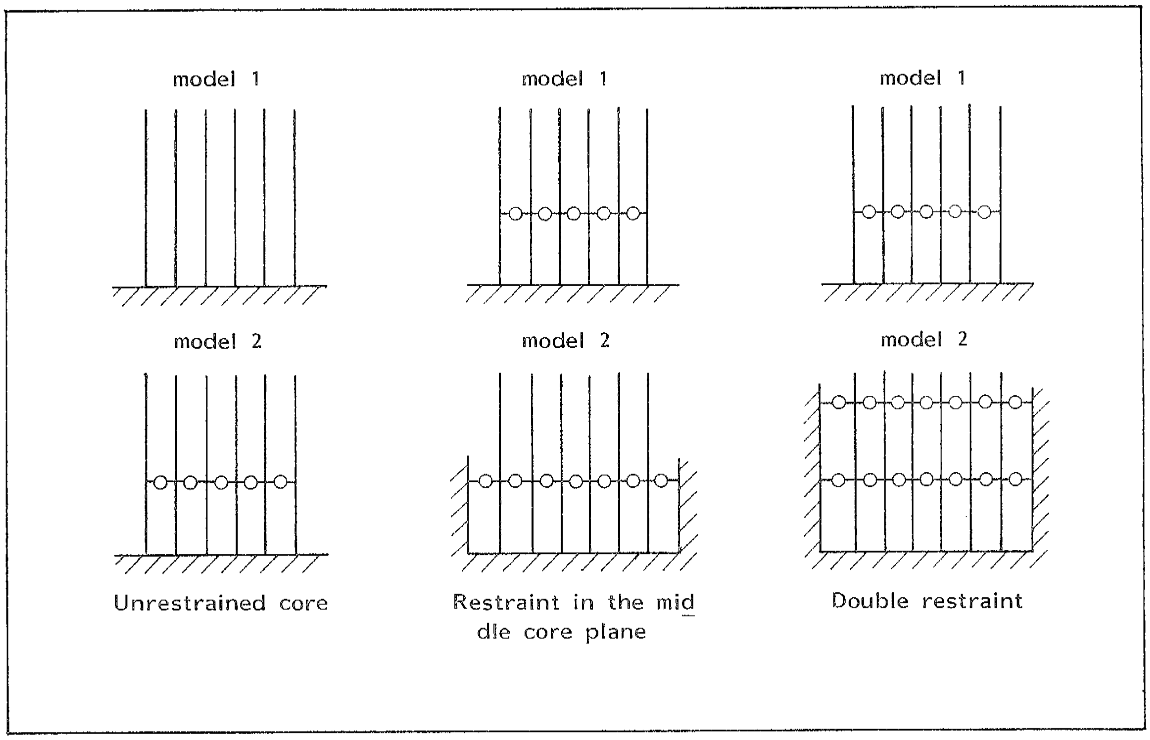

Fig 3 : First iteration linear core models

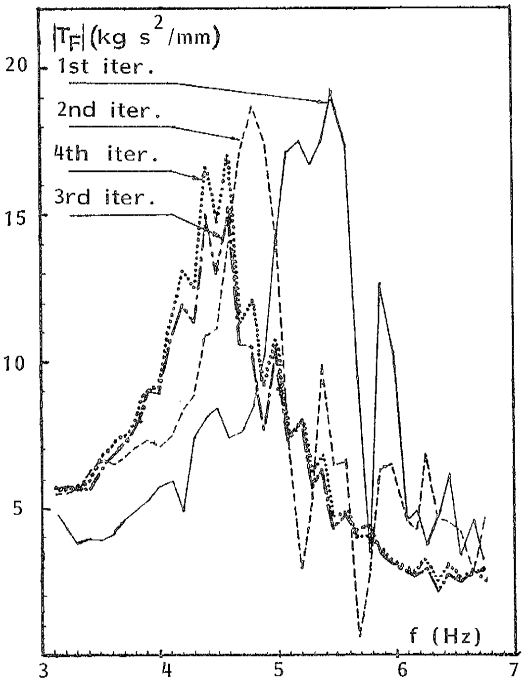

Fig 4 : Transfer function amplitudes of the reaction force at the various iterations in the case of a restraint structure located in the core middle plane

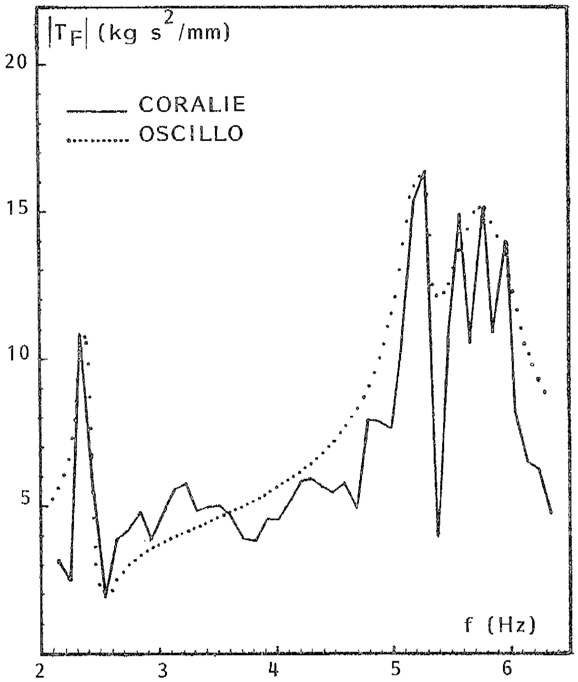

Fig 5 : Comparison between the transfer function amplitudes of the reaction force computed with CORALIE and OSCILLO in the case of double core restraint (4th iteration)