Dynamic and Seismic Behaviour of PEC Reactor Core Elements: Comparison Between Computed and Experimental Results

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SUMMARY

This paper describes the most important experimental results of dynamic tests so far carried out at ISMES, within an agreement with the Department of Fast Reactors of ENEA, on some mock-ups of PEC Fast Reactor Core elements in the frame of the activities for the seismic verification of the PEC core.

Furthermore, the linearization criteria of the single element vibrational behaviour are reported and comparisons are shown between experimental results obtained during some shock tests on couples of core elements and the numerical ones evaluated at ENEA.

The seismic verification is also briefly described with particular attention to the experimental program. Some remarks are given about the computer code used for the core analysis.

1. INTRODUCTION

According to the safety and operating requirements concerning a LMFBR, the seismic analysis of the Italian PEC Fast Reactor Test Facility is carried out by ENEA/DRV and NIRA to verify whether such reactor can be shut down and the residual heat can be removed in the case of the Safe Shut-Down Earthquake (SSE), and furthermore, whether the reactor structures remain functional in the case of the Operational Basis Earthquake. As regards the core, it has to be demonstrated that the control rods can be inserted and the core elements do not fail during the SSE and also, that the integrity of these elements is ensured up to the OBE |1|.

A computer code, which makes use of modal analysis, CORALIE, is applied by ENEA/DRV to calculate the core seismic response. The modes are computed considering the core elements as continuous beams, thus assuming that the effects of the internal non-linearities may be taken into account by viscous damping parameters and those due to the clearance at the foot both by viscous damping and by correction factors of the stiffness. Furthermore, to simulate the shocks effect, "spring-damper" concentrated bumper elements are introduced, and finally, added-mass and damping matrices are used for describing the fluid-structure interaction.

The performance of experimental tests was decided, both to provide the necessary input data and to validate the code and its hypothesis. The paper describes the experimental program, the related results obtained up to now and presents some first comparisons between numerical and experimental results.

2. DESCRIPTION AND PURPOSES OF THE PRESENT EXPERIMENTS

Experimental tests for the seismic verification of the PEC core are carried out at ISMES in Bergamo. More precisely, for those concerning the core elements, ISMES has been commissioned by ENEA/DRV, while those on the Control Rod Mechanism are carried out within the frame of a contract with NIRA.

The experimental research program for ENEA is splitted into three parts:

1) Tests in air on two simplified models reproducing only the outer geometry and the mass and stiffness distribution of the fuel and reflecting elements (Fig. 1) |2|, |3|.

2) Tests in air on six real element mock-ups (three fuel, two reflecting and one shielding element - Fig. 2) |3|.

3) Tests in water on large core configurations in order to evaluate the fluid-structure interaction effects.

Only the two first parts have so far been completed, the third one being in progress. Tests were performed on a shaking table, which excites at the base the elements mounted on a supporting grid.

Tests in air on the element mock-ups were performed measuring the displacements at the top, the strains at the foot and the accelerations at several points of the elements exciting these ones with three types of excitation:

- a monofrequencial sinusoidal excitation with increasing and decreasing frequency sweeps;
- a multifrequency steady state random excitation;
- a multifrequency transient excitation with time histories synthetized, starting from the floor response spectra at the level of the core supporting grid. These tests were conducted on six different couples and on a configuration of three fuel element mock-ups (Fig. 3).

The aims of the tests were:

- to investigate the linearity of the dynamic behaviour
- to evaluate the effects of the clearance at the foot
- to determine natural frequencies, damping or relevant amplification factors, both for each single element and for the configurations of elements
- to pinpoint the impact zones and the modalities of impact among the elements
- to measure the contact time and the acceleration in the impact zones.

3. EXPERIMENTAL RESULTS

Sine tests, performed at very low amplitudes to avoid damages to the elements, show a strong non-linear behaviour of the mock-ups and a very low reproducibility of results, in particular for the fuel and forced reflecting elements, due to possible interactions between the foot and the supporting grid at locations different from the contact spheres. As regards simplified models, the frequency response is strongly dependent on the excitation amplitude and on the clearance at the foot, and shows an increase in natural frequencies with increasing excitation amplitude and an opposite behaviour with increasing clearance at the same excitation amplitude (Fig. 4). The analysis of the amplification factors bears out the non linear behaviour, whereas the shape of the first mode is approximately constant |2|.

The multifrequency random excitation made it possible both to get higher peak accelerations of the same order of the seismic ones and to study more appropriately the non linear behaviour. In these tests the natural frequencies and the amplification values increase with increasing excitation amplitude, in a way similar to that shown by the simplified models; moreover, the natural frequencies tend to reach constant values when the excitation amplitude increases (Fig. 5). The study of the amplification factors bears out the same shape of the first mode found on the simplified models. The natural frequency values found for the seven configurations studied during transient shock tests are, in presence of shocks, approx. equal to those found on the single elements for the highest levels of excitation. Then the interactions between elements reduce the effects of the clearance at the foot with a consequent stiffening of the restraint.

As regards the study of the shocks, both impacts among inner parts and external liner and impacts between elements have been studied (Fig. 6). The transient of the acceleration response in the impact zones lasts about 30-70 msec and the duration of the first peak of the response is about 0.5 msec. The peak values of the response vary between 20 and 150 g's for internal impacts with peak values of excitation of 0.15 and 0.5 g, respectively. These values increase till 400 g's for external impacts with a peak acceleration of about 0.3 g. The duration and the shape of the acceleration response due to inner shocks is practically independent of the element studied, and as regards external shocks, it seems that both the configuration studied and the time-history utilized had little influence on the peak amplitudes of the acceleration response.

4. LINEARIZED MODELS OF THE SINGLE ELEMENTS

Since the measured first natural frequencies become quasi-constant at the excitation levels of interest for the seismic analysis (Fig. 5), linearized numerical models of the core elements could be evaluated.

The discrepancy between the measured and the theoretical results so far obtained (Fig. 5) are mostly due to the effect of the clearance at the foot, and also, for the reflecting mock-ups, to the stiffening effect of the tube located inside the hexagonal liner, containing the nickel blocks; thus, the linearization of the single elements behaviour consisted in defining for the foot zones and, in the case of the reflecting ones, also for the axial zones in which the aforementioned tube is present, a stiffness correction in order to obtain the first natural frequencies of each linear analytical model equal to the measured ones (Fig. 7) |4|.

5. COMPARISON BETWEEN COMPUTED AND EXPERIMENTAL RESULTS

The validity check of the procedure described in the preceding paragraph is in progress, by comparing the dynamic response computed with CORALIE to the measured one in the case of shock tests concerning both the simplified models and the mock-ups.

Fig. 8 shows the comparison for the frequency response of the couple of simplified models with sine excitation, obtained by introducing in the CORALIE model the vibrational parameters of each single element (stiffness and damping), evaluated on the basis of experimental results at equal excitation conditions.

Finally, table I shows the computed and measured top displacements in the case of excitation with given time history for couples of mock-ups, together with the values of the damping ratios assumed in CORALIE for the single mock-ups. For the couples of the same type elements (forced fuel elements), the experimental top displacements are very close to those calculated assuming a value of the damping ratio nearly equal to the measured one on the single mock-ups (1 - 1.2%). In the case of couples of different type elements, the measured amplifications are more affected than in the aforementioned case by the dynamic interaction due to the shocks; so an equivalent damping ratio was assumed in the analytical model in order to obtain comparable top displacements between analysis and tests. In any case, the adopted damping ratio does not depend on the particular couple studied, but it is of the same order for elements whose clearance at the foot is similar.

Such results confirm the adequacy of the linearization model adopted for the single elements, as shown by the good agreement between the measured and the calculated responses in the case of the couples.

6. CONCLUSIONS

The presently available results of the ISMES tests show that the behaviour of the single elements is strongly non-linear, the frequencies tend to constant values for excitation levels near to the seismic ones; this justifies the use of modal analysis in CORALIE, provided that appropriate corrections are applied to the element stiffness. These corrections, based on the results obtained for single models, appear to well reproduce the dynamic behaviour of the mock-ups couples, as shown by the results of some first calculations, carried out at ENEA/DRV. These conclusions will be verified by refining the theoretical model for the mock-ups on the basis of further very recent results, concerning strains and accelerations.

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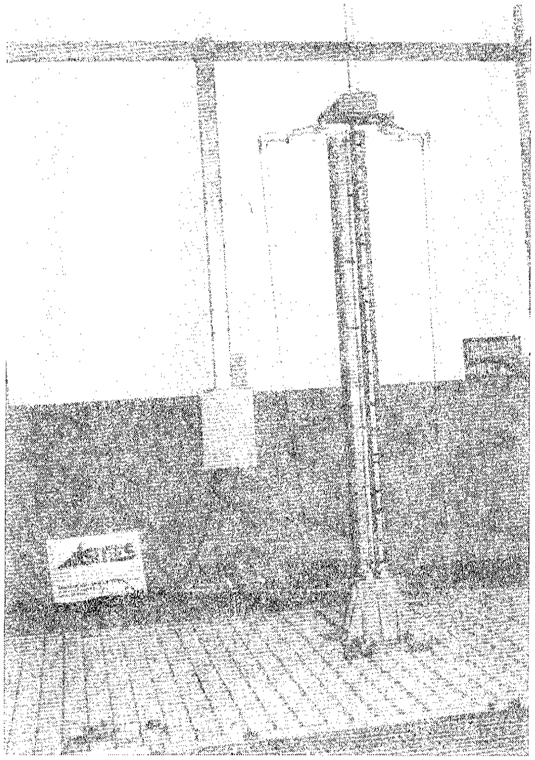

Fig. 1: Transient shock test on simplified models.

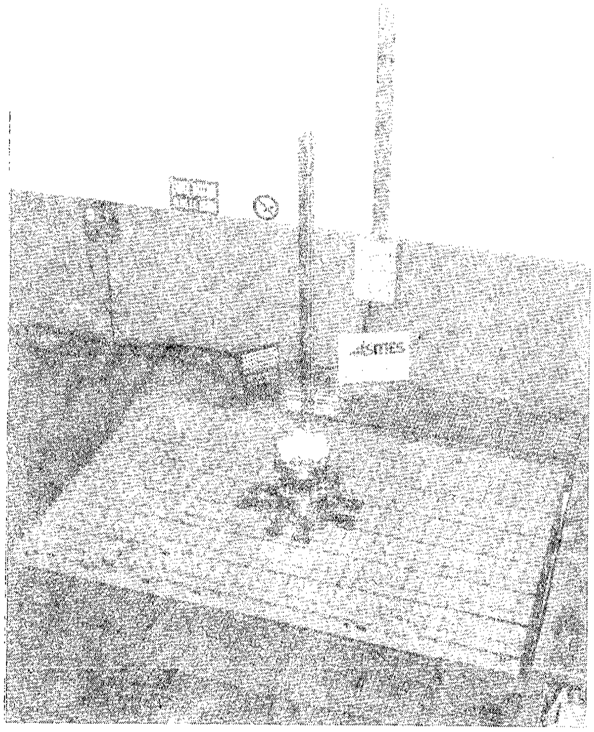

Fig. 2: Dynamic tests on the shielding element.

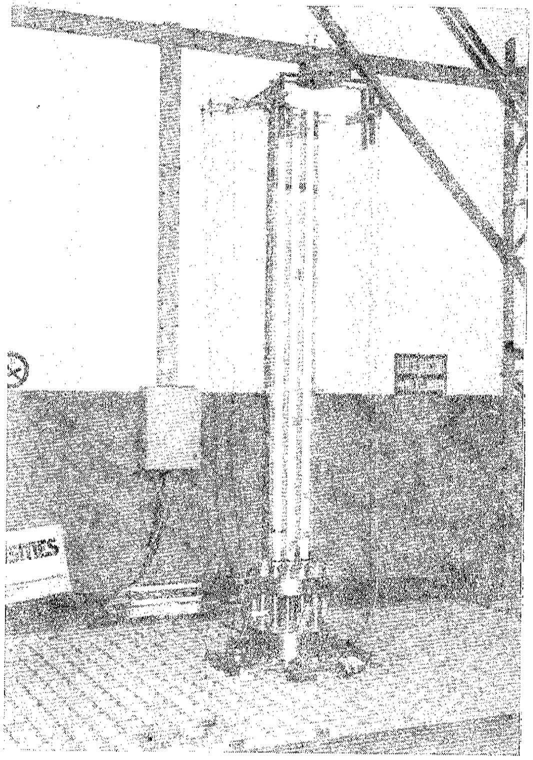

Fig. 3: Transient shock test on the configuration of three fuel elements.

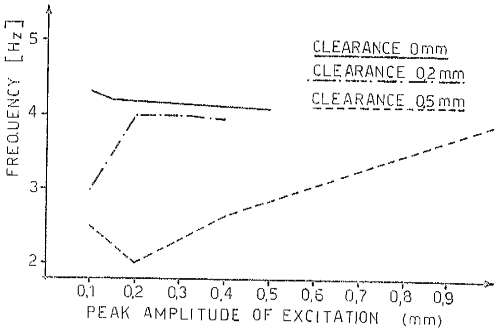

Fig. 4: First natural frequency of simplified reflecting model in presenceof clearance at the foot without antirotation devices.

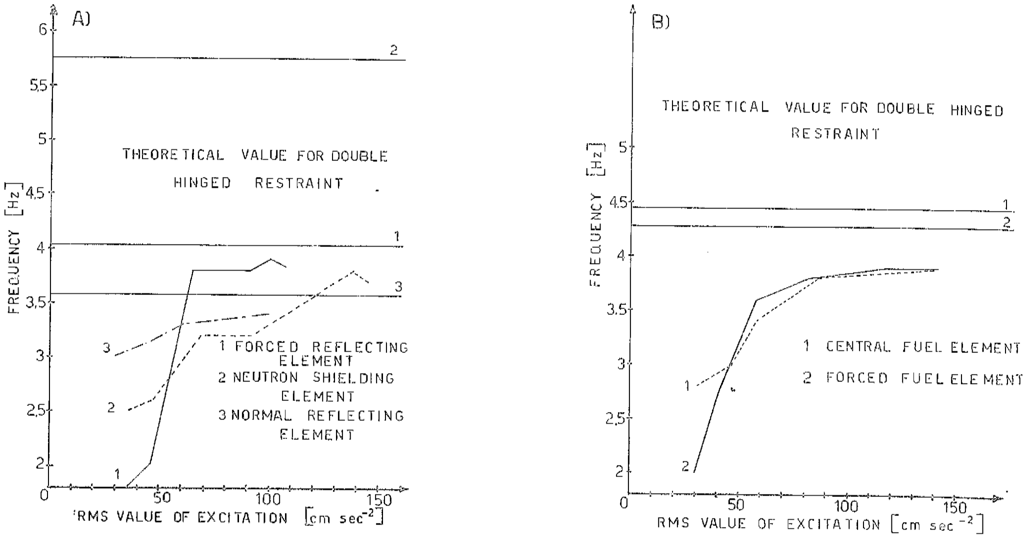

Fig. 5: First natural frequency values of mock-ups in random tests:

a) reflecting and shielding elements b) fuel elements.

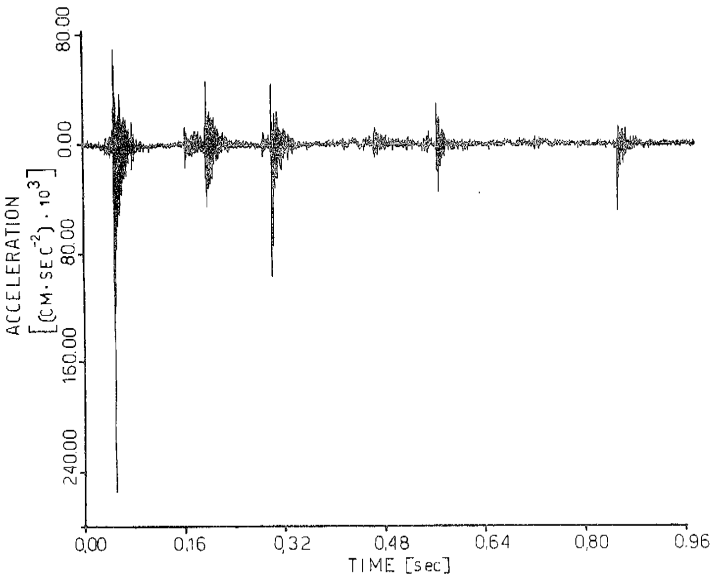

Fig. 6: Acceleration response during transient shock tests in an impact zone.

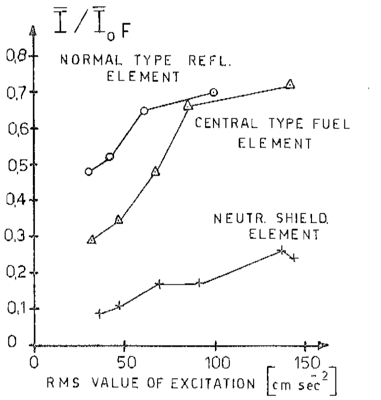

Fig. 7: Correction factors for the foot average moment of inertia ($\bar{I}_{of}$)versus excitation level for the random tests on single mock-ups models.

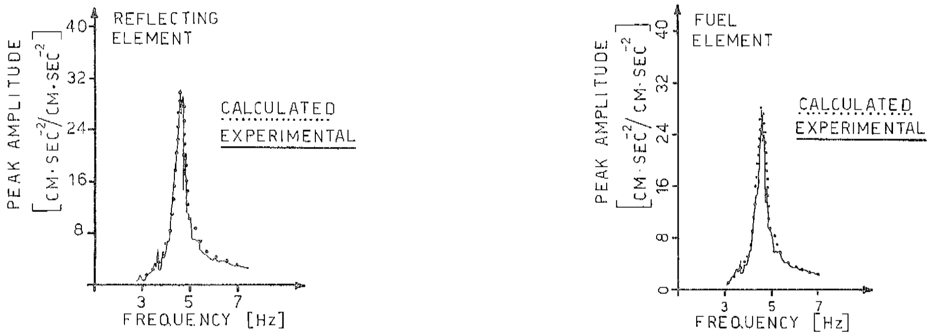

Fig. 8: Comparison between experimental and calculated transfer function for a sinusoidal shock test on simplified models.

PEAK GRID ACC. (g)	TYPE OF TIME HISTORY (*)	ELEMENT 1	ELEMENT 2	ANALYTICAL MODEL				TESTS	
				FRACTION OF CRITICAL DAMPING		TOP DISPL. (cm)		TOP DISPL. (cm)	
				η_1	η_2	S_{1c}	S_{2c}	S_{1m}	S_{2m}
0.16	a	CP1	CP2	0.95	0.95	3.05	3.05	3.08	3.01
0.16	b	CP1	CP2	0.85	0.85	2.67	2.67	2.70	2.64
0.22	b	CP1	CP2	0.85	0.85	3.68	3.68	3.74	3.63
0.18	a	CP1	CC	0.9	2	3.06	3.08	3.16	3.03
0.19	a	S	CP1	5.2	0.9	2.36	2.77	2.31	2.74
0.22	b	S	CP1	5.3	0.85	2.73	3.12	2.72	3.26
0.18	a	S	RN	4	1.9	2.51	2.55	2.43	2.54

(*) a = time history of 20 s obtained from a response spectrum with maximum frequency of 25 Hz
b = time history of 10 s obtained from a response spectrum with maximum frequency of 30 Hz

Table I: Comparison between experimental and calculated top level displacements (CP = forced-type fuel element, CC = central-type fuel element, S = neutron shielding element, RN = normal-type reflector).