Dynamic and Seismic Response in Air and Water of Prototypic Models of PEC Fast Reactor Core Elements

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Abstract

The paper presents the main results of recent experimental tests carried out by ISMES on behalf of ENEA for the seismic verification of the PEC fast reactor core. These tests were performed in air and water, simulating sodium, on single and coupled mock-ups of the various element types. Both the elements with the original geometry and those with the recent design modifications were analyzed. Some comparisons between computed and experimental results are also presented.

1. Introduction

A wide-ranging experimental programme is performed at ISMES on a shaking table to evaluate the response of PEC reactor core elements /1/. The first tests, performed in 1981-1982 concerned simplified models and quasi-prototype models, assumed to be dynamically equivalent to the various actual elements, all in full scale: these tests were performed in air on single models, couples and a group of three fuel elements /2, 3/.

The experiments were continued, performing tests in water on the cited models, tests in air on two corresponding actual fuel elements, and tests (mainly in water) on the new prototype elements (i.e. those with the recent modifications of the foot and shroud at restraint level, providing there a second set of pads /4/).

Furthermore, tests were performed to determine the dynamic loading acting on PEC fuel elements in the decay positions and the corresponding strains of the hexcans: these are presented in a separate paper /5/. Finally, experiments in water started at the beginning of 1985 for the evaluation of the fluid-structure interaction effects, analyzing core configurations of up to 19 elements.

2. Tests in air on the original mock-ups

The tests performed in air on single elements with the original design geometry /3/, showed that the first natural frequency values increase with increasing excitation amplitude, and that, in the case of multifrequency stationary excitation, they reach quasi-constant values, at the highest excitation levels, lower than those computed with the assumption of double-contact restraints (Fig. 1o). The mismatch between pre-test numerical results and experimental values was found to increase with increasing foot-can clearance. It was demonstrated that this effect can be simulated by correcting element foot stiffness. As concerns damping, this was found to decrease with increasing excitation, and with decreasing foot-can clearance (Fig. 1b): this confirms the role of foot-can clearances.
In the shock tests performed in air with seismic excitation for coupled elements, the first natural frequency values were slightly larger than the ones obtained for the single elements, even at rather low excitation levels: this was explained assuming that shocks among elements reduce the foot-clearance effects, thus stiffening the restraint.

Due to the mentioned slight difference between the results obtained for the single and coupled elements, the numerical analysis presented in ref. /3/ was based on the assumption that the first natural frequencies are equal to the maximum values detected for single elements. With this assumption it was demonstrated that the use of damping ratio of 1% in air taken in the design calculations /4/ is correct: in fact, although slightly lower values were obtained for some elements, larger damping values were determined for others (e.g. the neutron shielding and normal reflecting elements).

The same analysis, as reported in ref. /3/, was refined to take into account the frequency values obtained in seismic tests, thus removing the assumption previously made on first natural frequencies. The results of these calculations confirm the adequacy of the previous analysis and reliability of the values taken in the design calculations with regard to damping in air. Examples of comparisons between the results of measurements and those of calculations with the code CORALIE /4/, demonstrating the validity of the aforementioned conclusions, are reported in Figs. 2-4. These figures show the maximum displacement and maximum response frequency values as functions of the RMS values of the excitation, obtained for the two couples of different fuel elements (central and forced-types) and the group of three fuel elements. It is worth noting that the numerical results have been computed adopting for the forced-type fuel elements the damping value of 1.2% (Fig. 5), independent of the excitation level, according to the amplification values measured for the couple of the two forced-type fuel elements. Furthermore the damping values used for the central-type fuel element (Fig. 5) are also coherent with the measured amplifications. Similar results have been obtained for the other element couples.

3. Tests in air on two actual fuel elements

The tests on the two actual fuel elements (with the original geometry) have allowed the positive verification of the assumption of dynamic equivalence made for the previous models (Fig. 6). Furthermore, these tests were performed to very high excitations, so as to produce element displacements (66 mm at the top with respect to the supporting grid) much larger than those obtained in the previous tests (in which the seismic level was limited by the fear of damaging the models), and even larger than those which are allowed by the presence of the core-restraint ring. In spite of the large displacements, however, no damage was detected on the two elements after the tests. Moreover, it was noted that the first natural frequency has really reached a constant value at the highest excitations, slightly larger (approx. 10%) than the maximum one obtained in the previous tests, and approximately equal to that evaluated numerically with the assumption of double contact at element feet (Fig. 7).

4. Tests in water on the original mock-ups

The tests in water on the original prototype mock-ups were carried out using random and seismic excitation, to evaluate the coolant effects on the response of single and coupled elements. In seismic tests use was made of both the excitation applied in the previous experiments in air and that evaluated on the basis of up-to-date data /4, 5/. It was found that the coolant effects decrease with increasing excitation: this can be explained as a consequence of the clearance in the element foot. It was noted (Fig. 1a) that at the highest excitation levels, a decrease of the first natural frequencies is obtained, with respect to the values measured in air, which is in good agreement with the added mass theoretical correlations (approx. 0.6 Hz). The amplifications also show an effect of added
damping, which, however, is reduced at the highest excitation levels (Fig. 1b). Moreover, the response was found to depend not only on amplitude, but also on frequency content of the time-history applied.

5. Tests on the modified prototype elements

The tests described in the previous sections were repeated, mainly in water with new prototype mock-ups to evaluate the effects of the design modifications. Both multifrequency random and seismic excitations were applied on single and coupled elements. For seismic tests only the excitation time-histories evaluated with up-to-date data were used. The mock-ups had the actual feet and a second set of pads at the restraint level. Due to the results obtained in the previous studies, these new tests were performed allowing top displacements of up to 35-55 mm (again rather larger than those really possible in the core), which corresponded to the application of earthquakes of intensity comparable to that of TSS (i.e. Safe-Shutdown Earthquake). Moreover it should be noted that at the high levels of excitation reached in these tests the dependence of results from excitation type appears to be negligible.

The processing of these data is in progress. The first results confirm those obtained for the previous tests with regard to clearance effects in the foot and water effects. In spite of the high excitations, it appears that frequencies reach the theoretical values only for elements with small clearances in the feet (Figs. 0, 9). Furthermore, amplifications normally vary considerably with increasing excitation up to TSS (Fig. 10). This means that corrections to the foot stiffness are still necessary in the final design calculations, even at TSS, at least for the elements with large clearances in the feet; furthermore, different values of these corrections have to be applied to the case of 3/4 TSS /1/. Different damping values have also to be used for the two aforementioned reference earthquakes. With regard to the effect of the fluid, the results obtained in the previous tests of § 4 have been confirmed. Fig. 11 shows, in fact, that the frequency calculated in water with the theoretical added mass correlation, using the stiffness correction factor determined in air, mates well with the measured value at the excitation level (WMS acc. = 140 cm/s²) corresponding to the cited correction factor.

Finally, as concerns damping it is worth noting that the presence of water inside the elements and in the feet leads already to an increase of the damping ratio of the order of some percents (2-3%). This confirms the conservatism of the design calculations carried out up to now with damping of 5% /1, 4/: in fact, according to ref. /6/, the additive damping due to fluid flow in the small gaps among elements in large core configurations should be of more than 4% in the PEC case (see also Fig. 10).

6. Conclusions

The experiments and the related numerical analysis demonstrated the conservatism of damping values assumed in the design calculations and provided the necessary data for refining such calculations in both the TSS and 3/4 TSS cases. Furthermore, a contribution to the validation of the CORALIE code was given.

References

/1/ MARTELLI A.: "Methods for the seismic verification of a fast reactor core", Paper presented to this Conference (EK 2/1*).


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Fig. 1: Natural frequency and amplification values of the central type fuel element model in air and water (original design).
Fig. 2: Peak displacements of forced type fuel element for the couple with a second forced type f.e. (FF-FF) that with a central type f.e. (FF-CF) and a group of three f.e. (FF-CF-FF).

Fig. 3: Peak displacements of the central type fuel element for the couple with the forced type f.e. (FF-CF) and a group of three f.e. (FF-CF-FF).

Fig. 4: Maximum response frequency for the couple and the group of three fuel elements (FF-FF), (FF-CF), (FF-CF-FF).

Fig. 5: Fraction of critical damping of forced and central type fuel elements, FF and CF respectively.

Fig. 6: Natural frequency in air for the actual forced type fuel element with the original geometry and corresponding model (random excitation).
Fig. 7: Natural frequency values of the actual forced type fuel element with the original geometry (seismic excitation).

Fig. 8: Natural frequency values in water for the couple of two forced type fuel elements (random excitation).

Fig. 9: Natural frequency values in water for the neutron shielding element (seismic excitation).

Fig. 10: Amplification values in water for the couple of two forced type fuel elements (seismic excitation).

Fig. 11: Natural frequency values in air and water for the central type fuel element with random excitation (E/E₀ = foot stiffness correction factor in the calculation).