Vibration Analysis of a Pool Type LMFBR – Comparison Between Calculation and Full Scale Test Results

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SUMMARY

In order to predict the flow induced vibration levels of LMFBR vessels and internal structures, a full scale test program on SUPERPHENIX 1 Reactor has been defined.

The first part of this program consists of experimental determination of the characteristics of the structures in air main natural modes. The aim of these tests is to qualify a 3D modeling of vessels and associated structures used for calculation. Test conditions are particularly severe due the presence of a big number of resonance frequencies in a narrow band.

In a further step, tests in sodium configuration will be carried out and their results compared to calculation using the previous modeling and taking into account the fluid-structure interaction.

In parallel, new experimental data obtained on an hydroelastic mock-up will be used to characterize fluid flow excitation sources, to be applied to final modal results aiming the prediction of vibratory levels.

This paper concerns the first step of the program and presents :

- the 3 D in air calculation procedure and results,
- Air test procedure and results,
- Comparison between calculation and tests results.

This comparison is made by different ways for the two main structures studied, depending on the nature and complexity of their respective modes. It leads to the validation of various aspects of calculation and to guidelines for additional tests.

1. Description of Internal Structures, Hypothesis Used in the Model

The internal structures of a pool-type LMFBR consist mainly of several thin concentric axisymmetric vessels : main vessel, "conical redan" and "toroïdal redan".

This symmetry is broken by crossings fixed on the redans, distributed around the core and corresponding to the 8 heat exchangers, to the 4 primary pumps and to the instrumentation crossing (see figures 1 and 2). Pumps and heat exchangers crossings disposition is so that the assembly admit 2 plans of symmetry.

The lower extremities of the redans are connected to a very rigid diagrid which, for vibratory calculation, is assumed fixed. Then, in air, the "conical redan" with its crossings and the "toroïdal redan" with its crossings are separated structures. In sodium, these structures are strongly coupled by thin fluid sheets.

2. In Air Calculation Procedure

Computercalculation are based on substructuration-assembly procedure which allows to take advantage of the assymmetrical geometry of substructures and of the assembly's plans of symmetry. The procedure, developed by CEA/DEMT in TRISTANA CODE, consists of assembling substructures characterized by their free natural modes, which means that these modes are calculated without any boundary condition at the connecting nodes. The assembly is made by introducing stiffness couplings between these substructures' free modes. Assembly modes are determined on the modal basis formed by these free modes, and the error due to the modal basis truncation (error due to local deformation near the connecting nodes) is corrected by using the static responses of each substructure to forces acting at each connecting node , and introducing then an additional flexibility at these nodes. This procedure is described with more details in references [1], [2] and [3].

Free modes of axisymmetric substructures were calculated using CEASEMT CODE : AQUAMODE [4]. They are characterized by an azimuthal (circumferential) number n ($\cos n\theta$) and by an axial number m. Truncation frequency was taken at 25 Hz, number of nodes, elements and modes for each substructure are described in table I.

Assembly calculation were carried out using several hypothesis :

- the presence of instrumentation crossing has been neglected in order to maintain general symmetries ;
- the connection between each internal vessel (conical or toroïdal) and the crossings are introduced in the TRISTANA calculation by equality of the three components of the displacement on connecting nodes. No conditions are introduced on the rotation. This simplifying hypothesis was found effective by test validation ;
- limited connecting nodes number was taken : 11 and 12 for pumps crossings, 8 and 9 for heat exchangers crossings.

The 2 plans of symmetry allow to consider only a quarter of the structure with four groups of boundary conditions corresponding to four groupes of modes of the whole structure (see table II).

Assembly modes calculation results describe each of such modes by its table of substructures free modes contributions. Detailed information on assembly modes is obtained by plotting modes shapes according to different view angles and sections.

3. In Air Calculation Results

Results of air finite element calculation lead to the following remarks concerning the two assemblies :

- "Toroïdal redan" assembly

. Lowest mode frequency is 4.05 Hz and corresponds to a mode n = 6, m = 1 on the VERT* and thermal baffle with weak radial balancing of pump crossing.

. A big density of modes is found (34 between 4 and 8.1 Hz) corresponding mainly to the modes of the different shells associated to the toroïdal redan (VERT, thermal baffle and overfall shroud (see Fig. 3). Two main zones involve important movements of pump crossings (see table III).

. The first modes involving important movement of pump crossings arise between 5.13 and 5.93 Hz. They correspond to a mainly radial balancing of pump crossings, and couple modes n = 4 and n = 8 (m = 1) of redan shrouds existing in the same zone of frequency. They couple also important movement on heat exchanger crossings where occur balancing (n = 1) and circumferential shapes (n = 0 and 2).

. Second mode involving important movements of pump crossings arises at 7.59 Hz. It corresponds to a mainly tangential balancing of pump crossings, and is coupled with mode n = 3 of redan shrouds and with weak heat exchangers crossings balancing.

- "Conical redan" assembly

. Lowest mode frequency is 1.7 Hz. It corresponds to a mode n = 3, m = 1 on VERC* and redan, with already significant coupling between radial balancing and circumferential (on n = 0) shapes of pumps crossings.

. Modal density is found lower than for the toroïdal redan assembly (23 between 1.7 and 8 Hz). It appears that for major modes, important couplings occur between redan shroud modes, and between the redan and crossings. Pumps crossings intervene here by balancing and by circumferential shape (n = 0, 2 ; m = 1, 2), and heat exchangers crossings play an important role by balancing and circumferential (on n = 0) shapes.

. Many modes appear in this case with important movements on pumps and heat exchangers. They cannot be simply isolated as for the toroïdal redan. But the weaker density of assembly modes allows here to separate them into distinguished groups as indicated in table IV.

4. In Air Test Procedures

Two air test campaigns have been already held on SPX1 reactor in January and September 1982, and two other campaigns are scheduled for March and June 1983. The main aims of such tests is the determination of the characteristics of structure in air natural modes in order to qualify the 3D modeling and calculation described above. In another hand, strain gauges remaining permanently on reactor core structure have to be calibrated in order to provide reference elements for in sodium tests and for in service surveillance during reactor life.

Test conditions are particularly severe. Stepped sine, white noise and shock excitations have been used to obtain transfer functions. Even slow, stepped sine excitation has given best results because of the presence of a big number of close and coupled resonance frequences in a

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* VERT = External Shroud of the Toroïdal Redan.
* VERC = External Shroud of Conical Redan.

narrow band and because of stability problems of flexibly fixed shaker in low frequency range excitation . Tests have required the use of high performance servo-accelerometers. Furthermore, access problems have not allowed in all cases to excite the structures at the best point, and required to adapt the excitation technic.

For the first well excited resonances, a survey of mode shapes has been made all along a circumference of redan shrouds and on different points of crossings (see figure 4). The shape on vessels were later decomposed in Fourier series in order to obtain the azimuthal number n of shrouds free modes contributing in the corresponding assembly resonance (see figure 5).

Major interest of tests concerned conical and toroïdal redan assemblies. But measurements have been also made on diagrid and main vessel in order to verify coupling between these assemblies and the main vessel.

5. In Air Test Results, Comparison with Calculation

Results of first two campaigns lead to important conclusions concerning comparison between real and calculation model structures.

- "Toroïdal redan" assembly

Excitation where localized at the edge of pump crossings in order to show out mode with large movements on pump crossings. Shaker was fixed flexibly, and stepped sine excitation was most effective. Major results were the following :

. Lowest mode frequency was found at 4.15 Hz, and a big density of modes was found up to 9 Hz (see figure 6).

. The first modes involving important movements of pump crossings were found between 4.55 and 5.5 Hz. They correspond to a radial balancing of pumps crossings, coupled respectively with redan shroud free modes n = 5 pure (resonance at 4.64 Hz) and, n = 4 and 6 (resonance at 4.83, see figures 4 and 5). Radial connection between pump crossing and redan taken for calculation model is then validated, model seems to be slighly stiffer (10 % difference of frequency).

. The second mode involving important movements of pump crossings was found at 7.6 Hz as in calculation, corresponding to a tangential balancing of pump crossings. This confirms effectiveness of tangential crossings stiffness modelization.

. Concerning mode shapes on redan shrouds, detailed interpretation needs the results of future test campaigns. Available information leads to consider n = 5 as lowest mode azimuthal order, where calculation estimated it to be n = 6. Resonance frequencies seems to be 10 to 15 % higher than in model.

- "Conical redan" assembly

In this case, modes with large crossings movements are more difficult for interpretation. Major focus was then put on redan shroud, and white noise excitation on the edge of shroud was sufficient. Main results were the following :

. Lowest mode frequency is found at 1.58 Hz. It corresponds to a pure odd cosine n = 3 shape on redan shroud, and to an oblique balancing of pump crossing, shapes which were estimated by calculation.

. Modal density is found to be similar to calculation and first resonances can be also divided in 4 groups (see table IV and figure 7) :

- Group 1 of calculation modes was found between 1.58 and 2.2 Hz, with participation, of shapes n = 3 and 2 on the redan shroud, and of balancing on pump crossings.

- A well excited resonance at 2.67 Hz corresponds to calculation Group 2 (pure n = 4 on redan, weak balancing of crossings).

- A resonance at 3.55 Hz seems corresponding to Group 3 with important movements on pump an heat exchangers crossings.

- The 4th Group was found between 3.9 and 4.8 Hz. As in calculation, it is a dense and complexe group, and corresponds to major tangential movement on pump crossings.

From available information, we can conclude that conical redan free modes were well estimated (5 to 10 % confidence in frequency). Real structure seems to be lightly stiffer than model. Otherwise 3D effects introduced by crossings are similar in calculation and in model. But the complexity of such effects requires results of prospected additional tests for detailed interpretation.

- Global reactor internals modes

When exciting the two above described assemblies, acceleration measures were taken on main vessel and on the diagrid. A global core block internals mode, not taken into account in calculation, appears at 8.2 Hz. It corresponds to a global balancing of reactor internals supported by roof slab.

7 - Conclusion

First test results give good confidence in the 3D substructure calculation of reactor internals vibration modes. For the first well excited resonances, tested mode shapes on redans shrouds are in rather good accordance with calculation, resonance frequencies were found with 5 to 15 % confidence, but the toroïdal redan seems to be slighly stiffer than in model.

The most important aspect of the comparison between test and calculation results concerns the pumps and heat exchangers crossings and the 3D connected effects.

Pump crossings 3D connection with toroïdal redan is correct, the modelization is more effective concerning tangential movements than for radial movements. Conical redan pump crossings and heat exchangers crossings, as well as lowest modes of toroïdal redan needs prospected additional tests for interpretation. These tests will include mainly shock excitation on crossings and additional white noise and stepped sine excitation on shrouds edges.

References

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[2] JEANPIERRE GANTENBEIN, F., BERTAUT, C., AITA, S., "Calculation of Vibration of the Super Phenix Internal Structure", Third International Keswick Conference : Vibration in Nuclear Plant (11-14 May 1982).

[3] JEANPIERRE, F., LIVOLANT, M., "Système CEASEMT-TRISTANA - Principe - Notice d'utilisation", Rapport EMT/76/77 (1976).

[4] JEANPIERRE, F., BRABANT, F., LEPAREUX, M., "Système CEASEMT - Programme AQUAMODE", Rapport EMT/SMTS/VIBR/80/18, (1980).

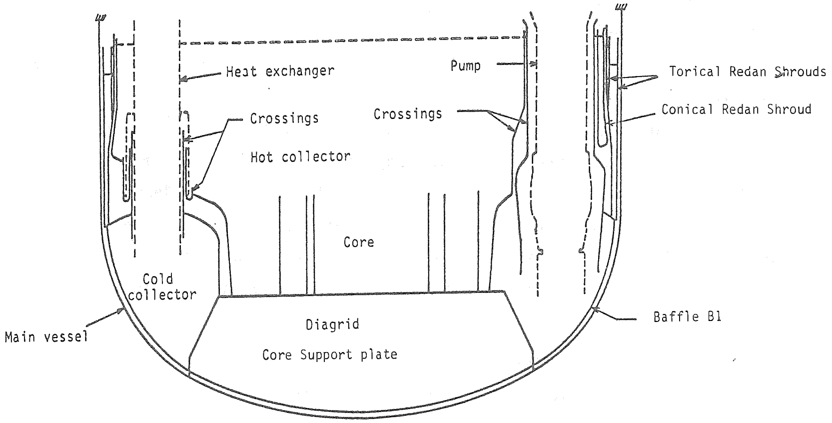


Figure 1 - SUPER PHENIX INTERNAL STRUCTURES

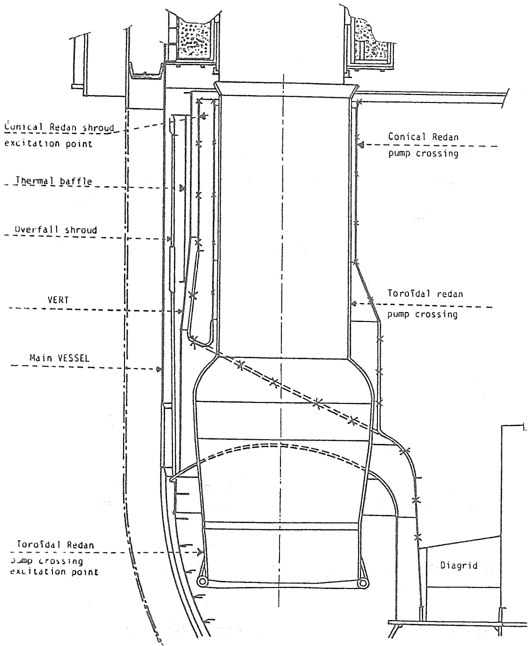


Figure 3 - SECTION OF REACTOR INTERNALS VIA PUMP CROSSINGS

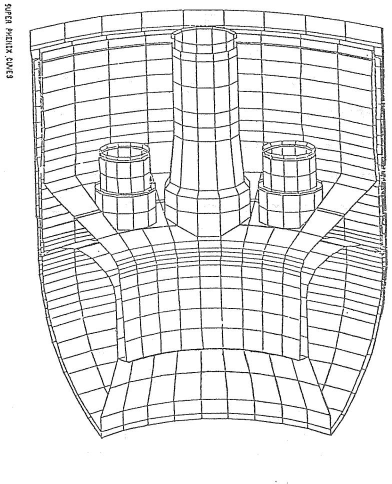


Figure 2 - GENERAL VIEW OF REDANS, SHROUDS AND CROSSINGS (QUARTER OF STRUCTURE)

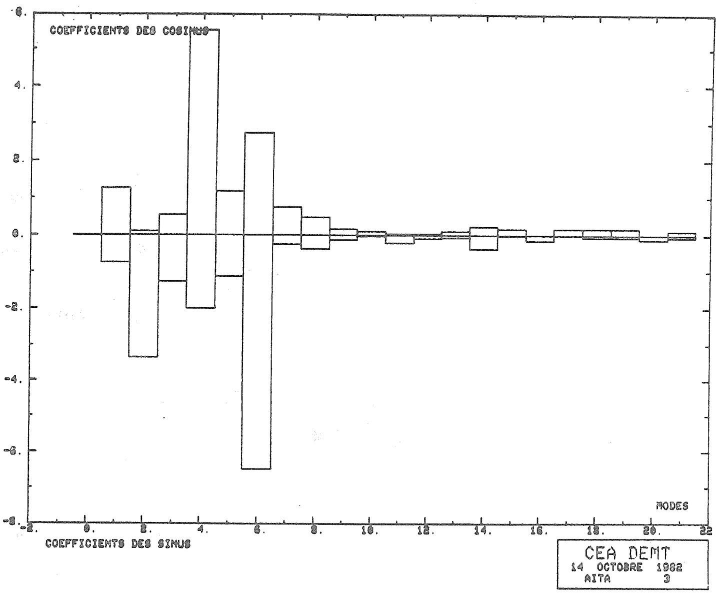


Figure 5 - FOURIER SERIES DECOMPOSITION OF TOROIDAL REDAN 4.83 Hz MODE SHAPE

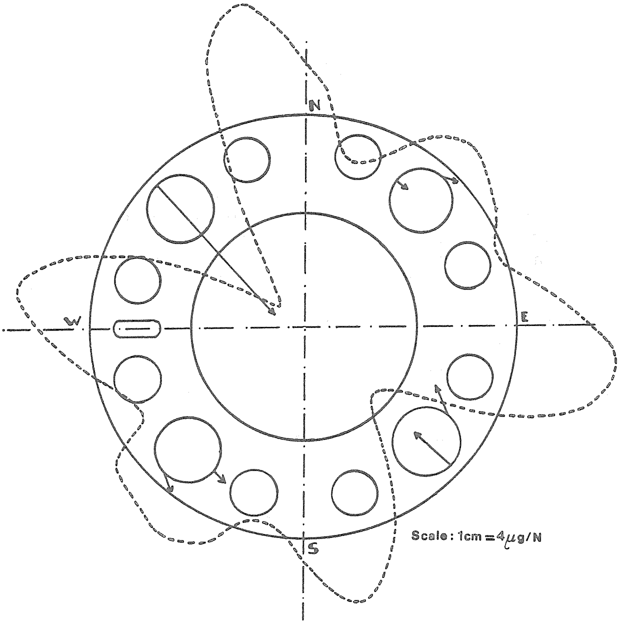
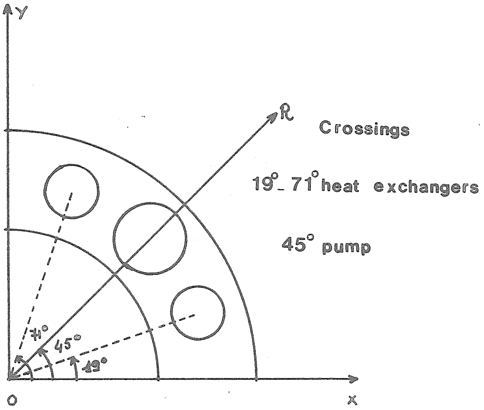


Figure 4 - 4.83 Hz TOROIDAL REDAN MODE SHAPE



Substructures	Nodes	Elements	Modes
Conical Redan Vessel	41	40	35
Toroïdal Redan Vessel	105	105	62
Conical Redan pump crossing	33	32	11
Toroïdal Redan pump crossing	47	46	8
Conical Redan heat exchanger crossing	29	28	9
Toroïdal Redan heat exchanger crossing	29	28	8

Table I - Number of Nodes, Elements and Modes taken for calculation of substructures

Group		Modal symmetry
1	Symmetric/XOZ and/YOZ	even* cosine modes
2	Antisymmetric/XOZ and /YOZ	even* sine modes
3**	Symmetric/XOZ, antisymmetric/YOZ	odd* cosine modes
4**	Antisymmetric/XOZ, symmetric/YOZ	odd* sine modes

* parity is related to azimuthal order numbers of vessels (conical or toroïdal redan) modes

** Groups 3 and 4 are symmetric/ZOR, they give same assembly frequencies. Only group 3 is calculated.

Table II - Geometry of structures and modes

Table III - Toroïdal Redan modes with important pumps crossings movements

Group	Frequency (Hz)	Number of modes	Redan shrouds mode shapes	Pump crossings mode shapes	Heat exchangers mode shapes
1	5.13-5.93	5	essentially n = 4 and 8 coupled on VERT and Thermal Baffle	Radial balancing	Balancing (n=1, m=1 and 2) and circumferential (n=0, m=1 and 2, n=2, m=1)
2	7.59	2	pure n = 3 on all shrouds	Tangential balancing	weak balancing

Figure 6 - TYPICAL TRANSFER FUNCTION ON TOROIDAL REDAN SHROUD

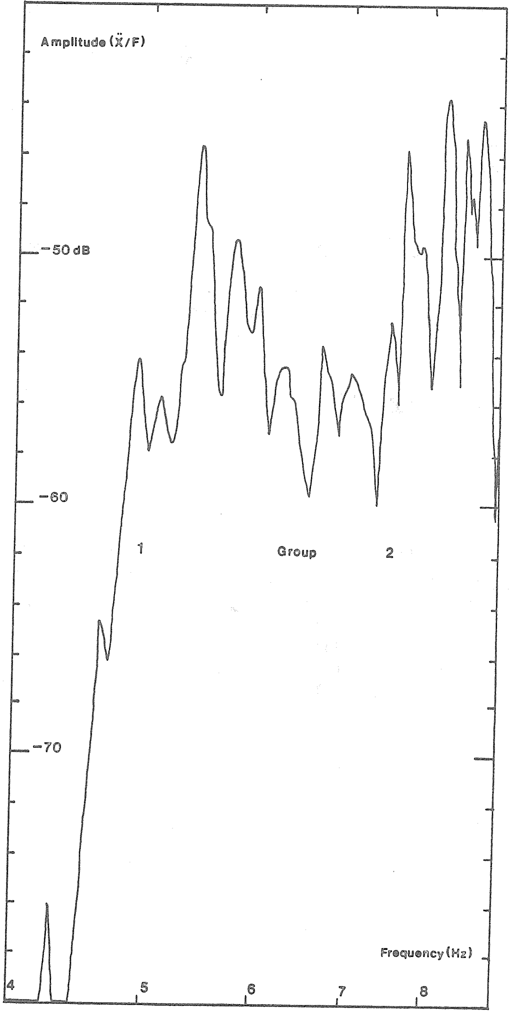


Table IV - Conical Redan Assembly modes groups (1.7 - 5.04 Hz)

Group	frequency band (Hz)	Number of modes	Redan shroud modes shapes	Pump crossings mode shapes	Heat exchangers crossings mode shapes
1	1.7 - 2.43	4	n = 3 and 2 pure	important radial and tangential balancing	weak balancing
2	3.02-3.06	2	n = 4 pure	weak balancing	negligible
3	4.44	2	weak n = 5* coupled	important tangential balancing and ovalization (n=2, m=2)	significant balancing
4	4.77-5.04**	4	complexe partification of n=4,5 and 6	important tangential balancing and ovalization (n=2, m=2)	significant balancing and ovalization (n=0)

* important movements on the redan itself.
** next resonances are over 6 Hz.

Figure 7 - Typical Transfer Function on Conical Redan Shroud.