INDUSTRIAL MODEL FOR THE DYNAMIC BEHAVIOR OF LIQUID METAL FAST BREEDER REACTOR (LMFBR) CORE

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ABSTRACT

Modeling the dynamic behavior of a Liquid Metal Fast Breeder Reactor (LMFBR) core is needed for seismic design purpose and more generally for the study of dynamic solicitations due to internal or external accidents. On LMFBR cores, special attention should be given to reactivity variation under such solicitations. The core of a LMFBR is generally constituted of long fuel assemblies with hexahedral sections immersed in liquid metal with relatively thin fluid layers between assemblies. The dynamic behavior of each fuel assembly taken alone is close to the one of a cantilever beam. Contact points between adjacent assemblies can appear under a dynamic loading, making the problem non linear. Most important of all, the thin fluid layers between assemblies imply a strong inertial coupling of each assemblies with potentially all the others. Despite the interesting capabilities of the finite element codes, such as the introduction of fluid elements coupled to structural ones, and the increasing performances of the computers, the modeling of the LMFBR core can not be addressed directly, while keeping the costs within reasonable bounds. This article first presents a way to simplify the problem and make it manageable by usual commercial computers. Then, the general dynamic behavior of the LMFBR core is described and illustrated. The influence of fluid-structure coupling is underlined.

INTRODUCTION

Liquid Metal Fast Breeder Reactor (LMFBR) designs are studied for the 4th generation of nuclear reactors. They are expected to significantly increase the amount of energy that could be extracted from both natural uranium and existing plutonium reserves. They do also have a potential for reducing the inventory of highly activated long duration nuclear wastes. Several experimental LMFBR have been built around the world, some of them are in operation today and some others are planned or under construction.

For future LMFBR, a very robust safety demonstration must be achieved. It is notably necessary to ensure that the effects of dynamic loadings on core can be managed. Several sources of dynamic loading on the core of such reactors have been identified. These sources include internal accidents, for example sodium boiling, and external accidents such as earthquakes or vibration induced by an airplane crash. Some important related safety issues are:

- Reactivity control: Unlike most of light water reactor designs, the core of a LMFBR is not in its most reactive configuration. In any situation, a large compaction of the fissile material must be avoided. Therefore, it must be demonstrated that under any kind of possible dynamic loading the core volume will not be decreased above a given limit. In order to limit possible reactivity insertion, relative movements between fissile subassemblies and absorber rods should be limited, and fuel pins break prevented (as fission gases may otherwise introduced reactivity as they replace sodium). Moreover, it shall be demonstrated that the control rods are able to fall within the core during a dynamic excitation.
- Core cooling capacity: The core is constituted of fuel assemblies in form of hexahedral tubes containing the fissile material. The liquid metal flows through these tubes and takes the energy out to the heat exchangers. Under dynamic loading, it must be demonstrated that the cooling capacity of the assemblies is not hindered.
- Material containment: The first barrier to prevent the spreading of fissile material to the environment is constituted by the fuel pins within the fuel assemblies. Under seismic loading, it must be demonstrated that these pins are not damaged to a level at which significant radioactive release from the core to the primary coolant could occur.

To deal with these issues, the designer must rely on numerical models of the core dynamic behavior. The first models in use did represent the core as a single row of beams, with the fluid represented as an added mass on each node of the beams. All the past French sodium reactor cores (Rapsodie, Phénix, Superphénix) have been designed with such models. More recently, several more complete models have been proposed by various authors, most of them researchers (references [2] to [5]), with particular consideration for fluid structure interaction effects. Such models present promising perspective regarding the robustness of the safety demonstration as they may serve to:

- Justify that safety functions are respected with significant margins for credible initiators,
- Identify optimized and suited core design features to limit the effects of dynamic solicitations, and enhance the core resistance to even more severe scenarios.

. The present paper describes the model that has been set up in AREVA for the study of the Sodium Fast Reactor (SFR) core. This model presents the advantages of relying on a commercial finite element code and on a simple theory, which makes it suitable for an industrial use.

The first part of the paper is dedicated to a general presentation of the physics that shall be accounted for in the modeling of the dynamic behavior of the LMFBR core. The second part describes the model that was set up and its functioning. The third part focuses on some illustrative results. Future ways of improvement of the model are given in the conclusion.

PHYSICAL PROBLEMS TO BE ADRESSED

Most of the LMFBR cores share some common characteristics. Their dynamic behavior may be different but the physics remains somewhat constant from one design to another.

The fuel assemblies are hexahedral tubes filled with fissile material, shielding and systems for fission gas expansion and flow orientation. The fuel assemblies are located at the center of the core. They are surrounded by a large number of other assemblies made of the same kind of hexahedral tubes and containing various materials. All assemblies are supported at their lower level. Their individual situation is close to the case of a vertical cantilever beam. The exact boundary conditions at the bottom and the top levels are design dependant.

The assemblies are arranged in a hexahedral pattern. Fig. 1 shows a top view of such pattern. Each assembly is itself surrounded by six others and contacts are possible between neighboring assemblies. Some contacts are effective under normal conditions so that there is at least one compact plane in the network of fuel assemblies, i.e. no decrease of the core volume can occur at this altitude. A protuberance (pad) on the hexahedral tube ensures the positioning of the compact contact plane. Under a dynamic loading, some contact can also occur at positions where the fuel assemblies exhibit their maximum deflection. In the case of SFR fuel assembly, there is a design contact level located approximately at mid height (above the fissile zone) and a second possible contact level under dynamic loading located a the top of the assemblies.

The fuel assemblies are crossed by the coolant flow with significant head losses. The possible dynamic excitation coming from this flow is not the topic of the present article and is considered disconnected from the dynamic accidental behavior of the core. Under dynamic loading, the flow might result in an increase of the "effective" stiffness of the assemblies in bending. It might also prove an important source of damping during the transient. Not considering the damping added by the fluid flow is a conservative assumption when evaluating the core response to an accidental excitation. The added stiffness is considered to be of secondary importance when compared to the effects of the environmental fluid.

Lastly all the assemblies are immersed into a pseudo-stagnant fluid. This fluid fills the gaps between neighboring assemblies and constitutes thin fluid layers between solid surfaces. These layers are typically a few meters high, a few centimeters wide and a few millimeters thick. This reduced thickness implies a strong dynamic coupling of the network of fuel assemblies: a small displacement of one assembly will immediately result in a significant change of the pressure field on all other assemblies, and especially the one in the vicinity of the displaced structure. The effect of the environmental fluid on the dynamic behavior of the core is of primary importance and can not be neglected.

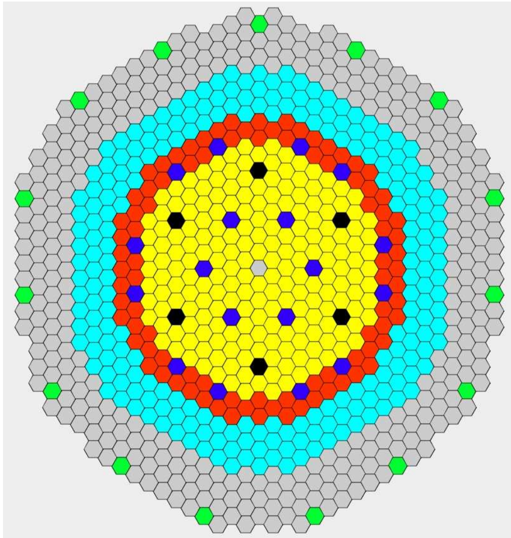


Fig.1: Top view of a network of hexahedral assemblies

MODELING STRATEGY FOR THE STRUCTURAL PART

Given the high number of assemblies located within a LMFBR core, the multiple possible contacts and impacts between these assemblies, the distorted topology of the fluid layers and the fluid-structure coupling, a large number of simplifications are required to make the dynamic simulation of the core behavior manageable. The simplifications that were adopted in the case of the SFR reactor are described hereafter.

First of all, each assembly was considered as a beam, with varying density and section along its length. A structural damping was assigned to the beams through the implementation of a Rayleigh type damping. Contacts between adjacent beams were modeled by non linear gap-spring-damper elements, which stiffness characteristics were determined by more local finite elements models. This stiffness is an important parameter of the model since the contact forces as well as the contact duration during the dynamic response depend on this value. The contact forces are outputs for analysis. The contact duration is useful both to analyze the impulses between assemblies and to check the adequacy of the time step of the numerical time integration. An overview of the beam mesh corresponding to the assemblies is given in fig. 2. The two planes with contact elements are identified in fig. 3.

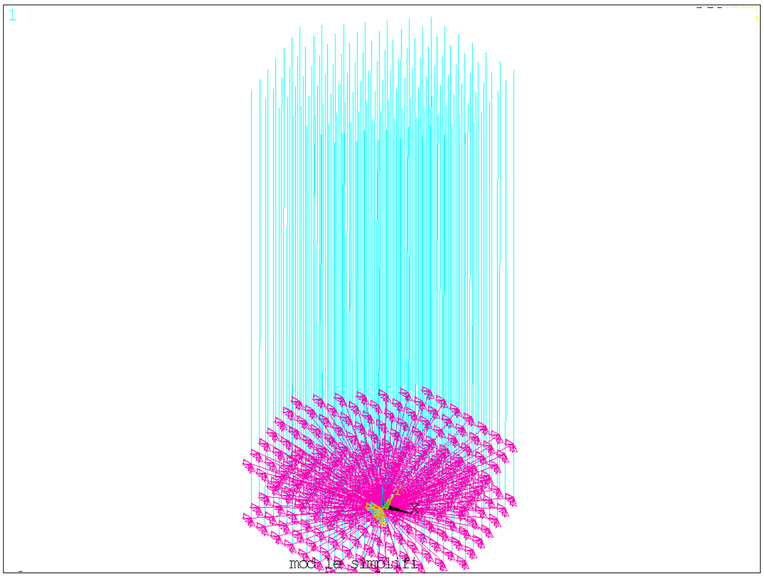


Fig.2: Hexahedral network of beams representing the assemblies

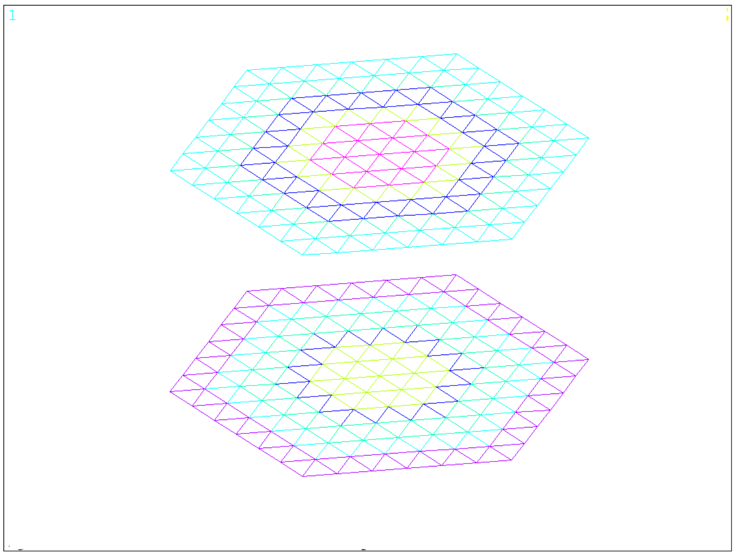


Fig.3: Spring-dampers contact elements

MODELING STRATEGY FOR THE FLUID-STRUCTURE INTERACTION

Several assumptions are made concerning the behavior of the environmental fluid. First of all, its viscosity is neglected. This is a conservative assumption. Then it is considered that the relative movements of adjacent assemblies remain sufficiently small for the physics of the flow in between to remain linear. Finally, the full Navier-Stokes equations describing the fluid behavior are reduced to the wave propagation equation:

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{1}$$

with *p* the pressure and *c* the celerity of sound within the fluid. The introduction of this equation into a structural model is achieved through purely acoustic elements. The nodes associated to these elements have a unique degree of freedom: pressure, except at the interfaces with solid structures, where additional displacement degrees of freedom are coupled to the structural ones. At the boundaries of the fluid domain, the variations of the pressure are directly linked to the mass of fluid accelerated by the structure through the equation:

$$\{n\}.\{\nabla p\} = -\rho_0 \{n\}.\frac{\partial^2 \{u\}}{\partial t^2} \tag{2}$$

In this equation, $\{\nabla p\}$ is the pressure gradient vector at the fluid-structure interface, $\{n\}$ is a vector denoting the direction normal to the interface, $\{u\}$ is the displacement vector of the fluid nodes located on the interface and ρ_0 is the fluid density. When the pressure spatial derivative is written in a discrete form and the equations are arranged into a matrix form, the previous equations become:

$$\lfloor M^P \rfloor\{\ddot{P}\} + \lfloor K^P \rfloor\{P\} = -\lfloor M^{fs} \rfloor\{\ddot{u}\} \tag{3}$$

where $\{P\}$ is the vector of the pressure degrees of freedom within the fluid and $\{u\}$ is the vector of the displacement degrees of freedom at the interface with the solid elements. The matrices $[K^P]$ and $[M^{fs}]$ are derived from the element's geometry and the previous equations. The $[M^P]$ matrix is diagonal and can be factorized by $1/c^2$.

On the structural side of the problem, the discrete equation of dynamics reads:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F_{ext}\}-[K^{fs}]\{P\} \tag{4}$$

with *[M]*, *[C]* and *[K]* the traditional mass, damping and stiffness matrices of the system, *{u}* the complete displacement vector, *{Fext}* the external forces applied on the structure (possibly including contact forces if they are not included in the stiffness and damping matrices) and $[K^{fs}]\{P\}$ the pressure force on the structure obtained by an integration of the pressure field at the interfaces. When equations (3) and (4) are concatenated, the global discrete equilibrium system to be solved is:

$$\begin{bmatrix}[M] & [0]\\ [M^{fs}] & [M^{P}]\end{bmatrix}\begin{Bmatrix}\{\ddot{u}\}\\ \{\ddot{P}\}\end{Bmatrix}+\begin{bmatrix}[C] & [0]\\ [0] & [0]\end{bmatrix}\begin{Bmatrix}\{\dot{u}\}\\ \{\dot{P}\}\end{Bmatrix}+\begin{bmatrix}[K] & [K^{fs}]\\ [0] & [K^{P}]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{P\}\end{Bmatrix}=\begin{Bmatrix}\{F_{ext}\}\\ \{0\}\end{Bmatrix} \tag{5}$$

An illustration of such fluid-structure model is given in fig. 4 for the SFR core. In such model, the highly distorted topology of the fluid volumes imposes a relatively high number of fluid elements. This profusion of elements and interfaces combined with the non symmetrical aspect of the problem and its non linearity due to the contacts makes it unsuited for an industrial use. Then it served only as a basis for the construction of a simpler model. It was also used to check that no information was lost by using the simpler model.

Fig. 4: View of the 3D acoustic fluid elements

The model simplification is based on the additional assumption that the core dynamic behavior is unaltered by the compressibility effects of the fluid. If the fluid is assumed incompressible, the $[M^P]$ term of eq. (3), which can be factorized by $1/c^2$ according to eq. (1), disappears. Then the pressure field in the fluid depends directly on the interfaces accelerations:

$$[K^{P}]\{P\}=-[M^{fs}]\{\ddot{u}\} \tag{6}$$

The effect of the fluid can be accounted for by introducing in the purely structural model an added fluid coupling matrix determined from the previous ones. The system becomes symmetrical and only the structural degrees of freedom associated to the beams are conserved.

$$[M^{fluid}]=[K^{fs}][K^{P}]^{-1}[M^{fs}] \tag{7}$$

$$\left(\left[M\right]+\left[M_{fluid}\right]\right)\left\{\ddot{u}\right\}+\left[C\right]\left\{\dot{u}\right\}+\left[K\right]\left\{u\right\}=\left\{F_{ext}\right\} \tag{8}$$

This simplification makes the calculation of the dynamic behavior of a LMFBR core more manageable without requiring the use of a dedicated program. Indeed, the transformation described in eq. (7) can be performed with any commercial FE code allowing an open access to the matrices of the fluid-structure model. Comparative modal and time history analyses have demonstrated that for low frequency excitations, such as a seismic loading, no difference appears in the results produced by the complete and the simplified model. For higher frequency excitations, the model is capable of determining the core response, which is essentially at low frequencies if the loading is completely determined. Pressure wave effects can no more be simulated with the simplified model.

RESULTS

Modal Analysis

If the contacts between assemblies are de-activated and all assemblies are considered identical, a modal analysis of the core without fluid coupling effect would exhibit N first bending modes at a same frequency f_1, N second bending modes at a same frequency f_2, and so on. N being the number of represented assemblies. The introduction of the fluid coupling effect through the adjunction of the $[M^{fluid}]$ matrix spreads the first bending modes over a wide range of frequencies (See Fig. 5). The lowest frequency mode is the global opening/closing mode (see Fig. 6a) of the core. It is the mode displacing the highest mass of fluid, logically resulting in a sharp frequency decrease compared to the "dry" modes (factor 2.8 in the case illustrated in Fig. 5). This mode, as well as the higher order opening/closing modes, can be excited by an internal dynamic event and are of prime importance for the study of the reactivity variation in such situations. The frequencies of the main global translational modes of the core are also affected by the presence of fluid, even though not as drastically as the opening/closing mode. Lastly, there is a global rotation mode of the core, involving a rotational bending of all assemblies around the center of the core (see Fig. 6b). In this mode the fluid layers are not squeezed at all. As a consequence there is no shift in frequency compared to the "dry" case.

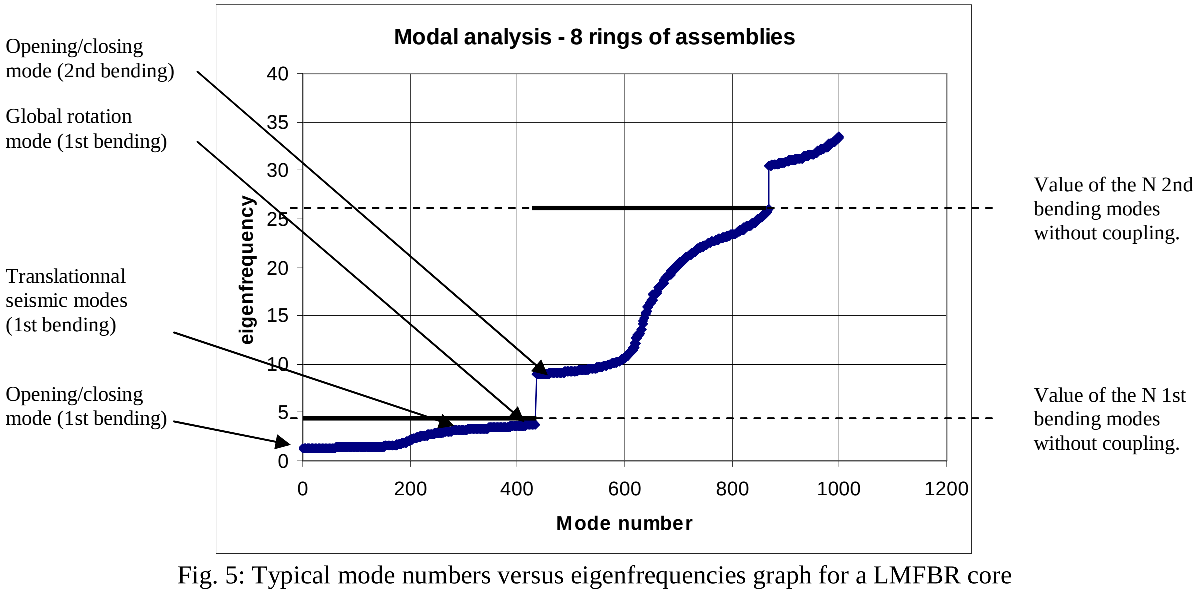
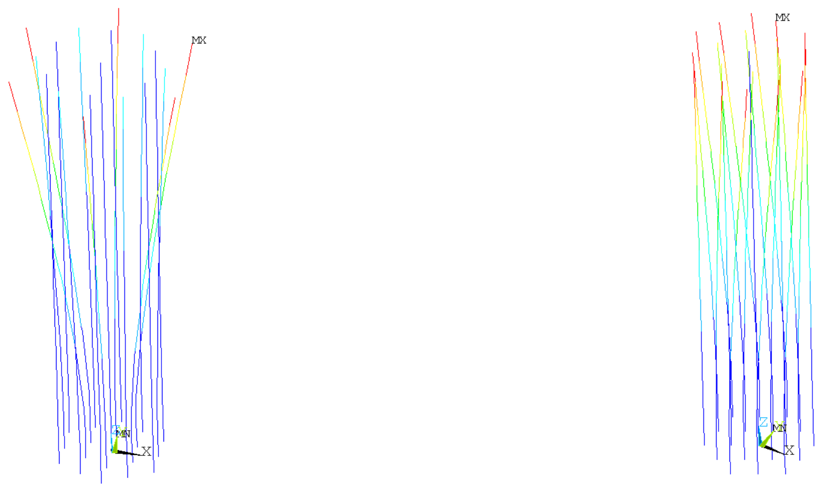


Fig. 5: Typical mode numbers versus eigenfrequencies graph for a LMFBR core



a) b)

Fig. 6: Illustration, with a reduced number of assemblies, of a) an opening/closing mode, b) a global rotation mode

Time History Analysis

Several time history analyses were performed using reduced SFR core model (about 300 assemblies instead of 1000). The reason for the limitation is that the $[M^{fluid}]$ matrix is a full matrix, which means that the number of terms increases as the square of the number of degrees of freedom, whereas matrices in traditional structural problems are sparse. The loadings included seismic acceleration time histories as well as initial velocity fields, representing a certain amount of kinetic energy transmitted to the assemblies. Various results were analyzed:

- Variation of the core volume, related to the reactivity variation during the transient.
- Maximum displacement of the upper part of the assemblies, related to the control rod falling time.
- Maximum torque at the boundary condition for the design of the assemblies
- Impact forces between adjacent assemblies, related to the pad design and to the acceleration levels transmitted to the internal materials.

Compared to a model with fluid represented as an added mass only, the dynamic contact forces between adjacent assemblies are reduced by the modeling of the fluid coupling. Indeed, all assemblies being coupled, the response of the core is always a global response, involving few relative displacements between neighbor assemblies. Even though two adjacent assemblies can have different stiffness characteristics, the fluid does not allow them to respond very differently to a same solicitation. Improving the model is then a way to decrease the importance of impact forces in the assemblies design. The variation of the core volume has also been found to be very dependant on the fluid modeling. Under a seismic excitation, there are some opening/closing modes combined with the translational modes.

The dynamic behavior of the core, as obtained in this study was found to be in global accordance with the experimental observations made on the SYMPHONY mockup, reference [6].

CONCLUSION

Modeling the dynamic behavior of the LMFBR core is needed for design purpose as well as for safety demonstration. The fluid-structure coupling effect is of primary importance in this modeling. A method has been proposed to properly account for the fluid inertial effect on the structure during a transient loading. This method makes use of standard finite elements codes capabilities and the underlying theory is simple. Still, in practice, it has not been possible to treat a full core at once and reductions of the number of assemblies have been necessary to obtain design results in a reasonable amount of time.

It is the opinion of the authors that a simpler representation of the network of fluid layers between assemblies is possible, even though such kind of representation is not readily available in standard finite elements codes. Ideally, inertial fluid layer elements with pressure degrees of freedom and pressure gradient depending on the relative acceleration of neighboring assemblies should be developed. Such elements would be compatible with existing acoustic elements to connect the network of fluid layers to the external fluid domain.

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