Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003
Paper # J02_6

Vibration Analysis of Reactor Assembly Internals for Prototype Fast Breeder Reactor

P.Chellapandi, S.Jalaldeen, R.Srinivasan, S.C.Chetal and S.B.Bhoje

Indira Gandhi Centre for Atomic Research, Kalpakkam-603 102, India.

ABSTRACT

Vibration analysis of the reactor assembly components of 500 MWe Prototype Fast Breeder Reactor (PFBR) is presented. The vibration response of primary pump as well as dynamic forces developed at its supports are predicted numerically. The stiffness properties of hydrostatic bearing are determined by formulating and solving governing fluid and structural mechanics equations. The dynamic forces exerted by pump are used as input data for the dynamic response of reactor assembly components, mainly inner vessel, thermal baffle and control plug. Dynamic response of reactor assembly components is also predicted for the pressure fluctuations caused by sodium free level oscillations. Thermal baffle (weir shell) which is subjected to fluid forces developed at the associated sodium free levels is analysed by formulating and solving a set of non-linear equations for fluids, structures and fluid structure interaction (FSI). The control rod drive mechanism is analysed for response under flow induced forces on the parts subjected to cross flow in the zone just above the core top, taking into account FSI between sheaths of control & safety rod and absorber pin bundle. Based on the analysis results, it is concluded that the reactor assembly internals are free from any risk of mechanical as well as flow induced vibrations.

KEYWORDS: FBR internals, mechanical vibrations, FIV, hydrostatic bearing, pump induced vibrations, pressure fluctuations, FSI, sloshing, fluid-elastic instability, thermal baffles.

INTRODUCTION

The reactor assembly (RA) of 500 MWe capacity Prototype Fast Breeder Reactor (PFBR) is shown in Fig.1. Its main out-of-core structures are main vessel (MV), inner vessel, control plug (CP), control and safety rod drive mechanism (CSRDM), diverse safety rod drive mechanism (DSRDM), primary sodium pump (PSP), intermediate heat exchanger (IHX) and thermal baffles (TB). These structures are basically thin walled slender shells (diameter/thickness ratio ranges 100 – 650), immersed in liquid sodium. MV carries ~1150 t of primary sodium mass. The inner vessel and TB are separated by relatively thin annulus of liquid sodium (annulus gap-diameter ratio: w/D ~ 1/100). Another special feature is the existence of free fluid surfaces which is the source of sloshing phenomena during normal operation. The structural wall surfaces are subjected to random pressure fluctuations which can cause significant displacements of reactor internals by virtue of their high slenderness ratio. These features are responsible for their lower natural frequencies (5-15 Hz) and sensitivity to vibrations. Even though the vibration level of PSP is controlled, the induced forces at the support locations: one at roof slab and another at spherical header nozzle, can cause significant vibrations of the structures supported by them, possibly due to resonance. The vibration originated either from PSP or from flow induced vibration mechanisms may cause unacceptable displacements of structures from the point of view

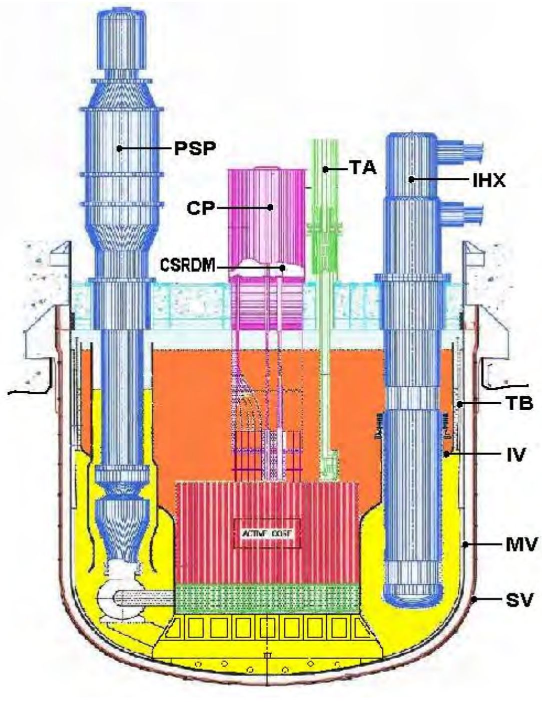

Fig.1 Schematic of RA

of reactivity oscillations, mechanical interactions and high cycle fatigue due to fluctuating stresses. In some special cases, the fluctuations due to mechanisms such as fluid-elastic instability leads to a rapid damage of the structures.

The type of vibration problems addressed above call for identification of excitation forces, formulation of special governing equations and detailed analysis with fluid structure interaction and sloshing effects, particularly for the components such as PSP, inner vessel, CP, CSRDM and TB. The summary of analysis carried out for these components are presented in this paper. For other components such as IHX and internals of CP, for which flow induced vibration (FIV) is of concern, are checked as per ASME Appendix-N [1] which are not covered here. The paper does not address the vibration problems of the core components.

ESSENTIAL FEATURES OF COMPONENTS

In the RA, the inner vessel separates hot and cool pools of primary sodium. It is a self standing vessel bolted to grid plate (GP) and consists of lower and upper cylindrical shells connected by a conical portion called redan. There are 6 stand pipes in the redan to provide passages for IHX and PSP. The outer diameters of these shells are 12.2 m and 6.35 m respectively and having the thickness of 15 mm. But the redan is of 20 mm thick. The overall height is around 9.1 m. A ring stiffener (50 mm width and 20 mm thick) is welded at the free edge of the upper shell.

MV is cooled to maintain its temperature below creep regime (~ 700 K) by sending a fraction of cold sodium through an annular space between main vessel and weir shell. MV cooling circuit consists of feeding collector through which sodium flows upward and restitution collector from which sodium flows down to join the cold pool. The nominal gap between the MV and outer baffle is 90 mm, between outer and inner baffles is 95 mm and between inner baffle and inner vessel is 100 mm. The level difference between feeding and restitution collector is 700 mm which is the fall height of the coolant flow over the weir shell.

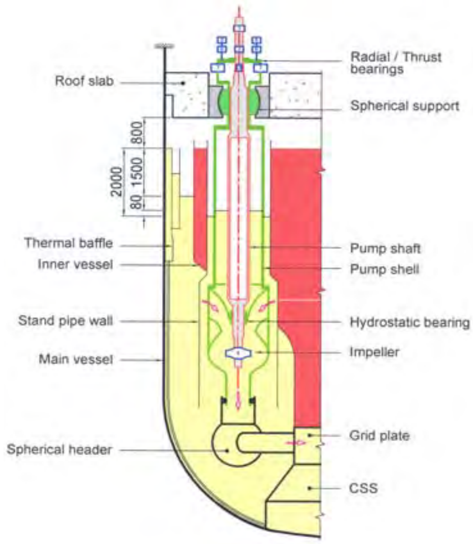

Fig.2 Schematic of PSP located in RA

Two PSP operating in parallel circulate the sodium (8.26 m^3/s at 75 mlc head) to the core. The PSP runs at a nominal speed of 590 rpm which can vary between 15 and 100 %. The pump assembly consists of pump shell and shaft which is located inside a standpipe penetrating into the cold pool. The impeller is mounted on the shaft and the suction bell is attached with the pump shell, at the bottom. The shaft and pump shell are connected at the top by an assembly of thrust and radial bearing. There is a hydrostatic bearing (HSB) between the shaft and suction bell, just above the impeller level, to align the shaft precisely along the central line under all operating speed of the pump within the radial clearance of 400 μ. Thus, the shaft rotates freely within the shell. The shell, in turn, is supported on the spherical bearing assembly at the top so that the shell can tilt to accommodate the cumulative radial expansion of the header, primary pipes and grid plate assembly. The discharge pipe which is attached with the pump shell, is inserted into the nozzle of the spherical header with a close tolerance. The flange of the spherical support is bolted to the roof slab (RS) to ultimately transmit the entire loads to the roof slab. The pump shaft is coupled to the drive motor shaft by means of a flexible coupling. Fig.2 shows the schematic sketch of PSP considered for the analysis.

The CP is positioned just above the core to provide passages for CSRDM and Diverse Safety Rod Drive Mechanisms (DSRDM), core monitoring thermocouples, sampling tubes and neutron detectors. It comprises of skirt assembly (parts immersed in sodium), middle assembly (portion which houses thermal shields and top plate) and upper portion which contains drives. The skirt portion is basically a shell with shroud tubes and intermediate plates called stay plates. It is positioned just above the core top. Shell as well as shroud tubes have appropriate perforations to optimize the flow to CP. A fraction of core flow (~10 %) passes through annular spaces between shroud tubes and CSRDM/DSRDM, comes out through perforations on the shroud tubes and finally emerges from the CP through the shell perforations. The outer diameter of shell is 2250 mm with 10 mm wall thickness. CP is supported on small rotating plug (SRP).

There are nine CSRDM in the reactor core to start, control and scram the reactor. Each CSRDM consists of control and safety rod (CSR) and its driving mechanism.

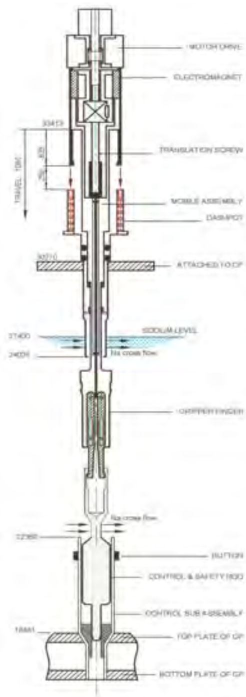

Fig.3 Schematic of CSRDM

The mobile assembly which actuates the fingers to hold the CSR is the main part of the driving mechanism. It, in turn consists of finger gripper mechanism, gripper operating rod (GOR) and translational tube. The GOR is housed within the translational tube connected at two extreme elevations, which transmits the rotary motion of the spline shaft driven by motor in the course of normal reactor control. The lower part of the translational tube is guided by an outer sheath which is the stationary part supported at the top plate of CP. The top end of the translational tube is connected to the guide tube which is guided by rails. Under normal operating condition, the guide tube is engaged with the electromagnet, which is acting as a fixed point as far as translational tube is concerned. For achieving the reactor scram, the electromagnet de-energises, guide tube detaches and the translational tube drops down inserting the CSR rapidly inside the control SA sheath. The translational tube is a flexible tubular structure covering the length of ~ 10 m from the top fixed point to the bottom point which is connected to the finger gripper mechanism and travels over the distance of 1085 mm from the top position to shutdown the reactor. The CSR consists of mainly absorber pin bundle sheath with top and bottom coolant passage tubes on either side. Under reactor shutdown, the entire CSR is within the CSR sheath, supported on the resting piece, with the bottom coolant passage tube fully inserted in to the central hole of the CSR sheath body. Under normal operating condition, the translational tube which carries the CSR is moved upward to its top position, the top coolant passage tube is fully projected above SA top and a portion of bottom coolant passage tube (~ 300 mm length) remains within the central hole of the CSR sheath body. Fig.3 shows the schematic sketch of CSRDM.

ANALYSIS APPROACH

The above mentioned components are analysed for mechanical and flow induced vibrations. The source of mechanical excitation is PSP vibration. Hence, the PSP is analysed first for the excitation forces caused by PSP unbalance and the results of analysis provides the data for checking the acceptability of vibration amplitudes and resonance condition for the shaft. Besides, it provides excitation forces at its supports on roof slab and at the spherical header nozzle joint, for which the RA is analysed subsequently, to determine the dynamic responses of various components. The RA is also analysed for the pressure fluctuations caused by sodium free level oscillations. The weir shell is analysed for the internal forces, generated on the sodium free surfaces due to coupling of sloshing modes in the feeding and restitution collectors. Finally, CSRDM is analysed for the excitations arised due to lift force generated across the top coolant passage tube under vortex shedding mechanism. The basic input data for the investigation are the natural frequencies and their associated mode shapes, which are determined including the effects of fluid structure interaction and sloshing of sodium free levels using the computer code CASTEM 3M. This code is also used for the dynamic response analysis of RA components including CSRDM, except PSP. For the analysis of PSP including gyroscopic effects as well as for the fluid-elastic instability analysis of TB, special purpose computer programs developed in-house were used.

VIBRATION ANALYSIS OF PSP

A single PSP is considered along with RS, MV, core support structure (CSS), GP, primary pipe along with the spherical header. The flywheel and the motor are not included since their loads are transmitted to roof slab directly. This implies that the stiffness offered by flexible coupling is ignored in the analysis, which is a conservative assumption. The shells, flanges and other connecting structures above the radial and thrust bearing are idealized as masses placed at their appropriate mass centers with rigid link connection. This ensures the conservation of mass and momentum. The entire structure is modeled with 3D beam elements. The main vessel, CSS, GP and the core are also modeled with 3D beam elements by preserving overall stiffness and masses so as to simulate the fundamental frequency. The finite element model consists of 71 nodes and 68 beam elements, apart from spring elements for HSB. The stiffness of roof slab and radial bearing are assumed to be rigid in radial direction. At the connection between the roof slab and the spherical support at the top and, as well as at the connection between the pump shell and header nozzle at the bottom, high stiffness elements are introduced to extract the forces transmitted by the pump to the roof slab and the primary pipe header respectively. The finite element mesh indicating the nodes, elements, stiffness and dampers for HSB, spherical support, rigid links, springs and lumped masses is shown in Fig.4. The structure is fixed at the reactor assembly support.

Natural frequencies are calculated assuming that the eccentricity of the shaft is zero at various speeds. The coupled mode involving 3 deformations:

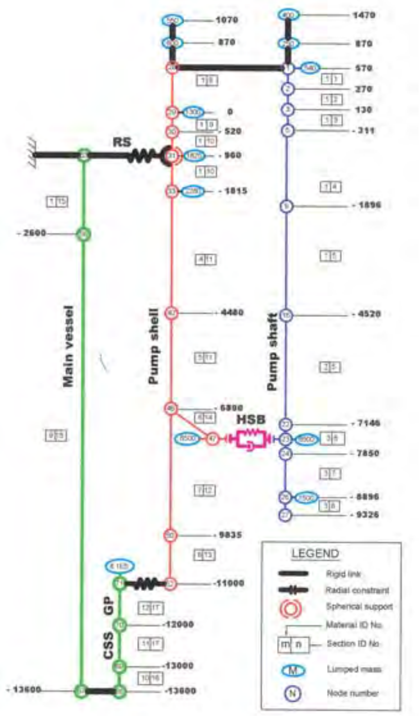

Fig.4 FE Mesh of PSP

(i) predominantly the bending of the shaft as cantilever beam due to relatively low stiffness contribution by HSB, (ii) bending of shell as simply-supported beam at two supports one at the top spherical support and another at the bottom spherical header and, (iii) swaying of main vessel is an important mode (Fig.5). The natural frequency associated with this mode shape is obtained for various operating speed. At the minimum speed of 90 rpm, the shaft frequency is ~2 Hz, close to the fundamental frequency corresponding to cantilever beam (shaft). At nominal operating speed, under the assumption that there is no eccentricity, the natural frequency of shaft is 9 Hz. which is close to normal operating frequency of the shaft. However, while running, the bearing develops higher stiffness and hence the frequency goes up. In view of stiffness variations with speeds, the resonance is investigated by determining the dynamic response of the shaft at HSB under various operating speeds which is given in the subsequent paragraph.

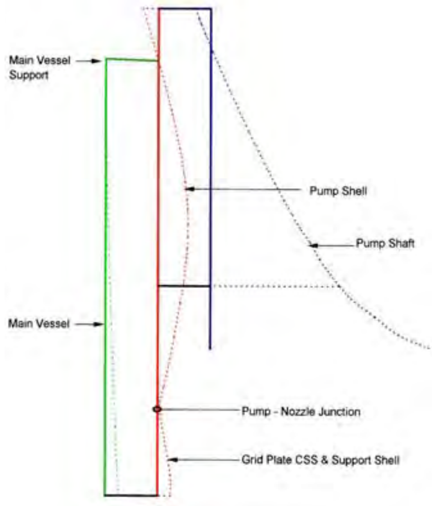

Fig.5 Critical PSP mode shape

The excitation source is the centrifugal force due to mechanical unbalance caused by manufacturing misalignment. The misaligned shape is assumed as vibration mode shape corresponding to 9 Hz. The product of mass and eccentricity is 0.260 kg-m for the unbalanced condition which is distributed based on product of modal mass and modal displacement at each node along the shaft, corresponding to shaft frequency. Applying the components of centrifugal force, the resulting dynamic equilibrium equations are solved by Newmark-β method (direct integration) to obtain the vibration responses for various speeds.

The locus of centroid of the shaft at HSB elevation (orbit plot), followed to attain the steady state condition is shown in Fig.6, which shows that the peak displacement of shaft at HSB location is 60 μ. The peak shaft displacements at various speeds are depicted in Fig.7 which clearly indicates that the resonance occurs at 700 rpm. Thus, there exists a margin of 1.2 on the nominal speed against resonance. The maximum amplitude at resonance, however, is limited to 160 μ which is less than the radial clearance of 400 μ. This implies that there is no metal to metal contact at HSB over the operating range including 20 % over speed. Thus, the analysis ensures smooth operation of PSP over the entire operating speeds.

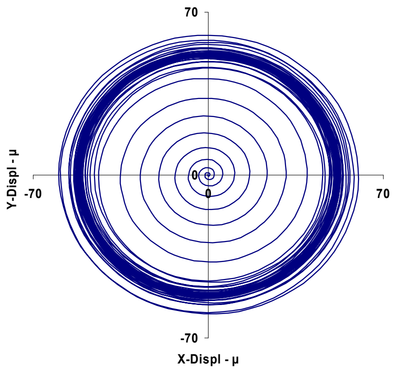

Fig.6 Orbit plot at 590 rpm

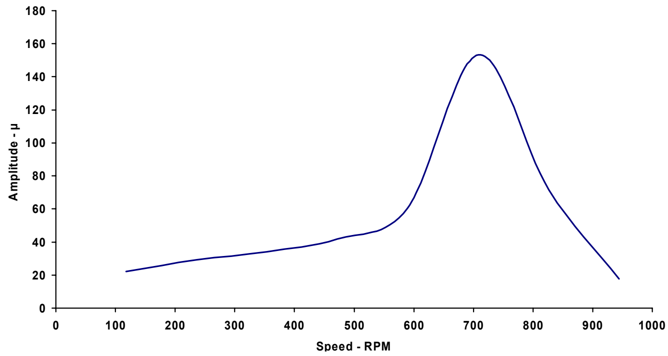

Fig.7 Peak displacement of shaft

VIBRATION RESPONSE OF RA UNDER PUMP INDUCED EXCITATIONS

The dynamic forces developed on the roof slab and on the pipe header at normal operating speed (590 rpm) are shown in Fig.8. The peak value is less than 3 t at RS support and less than 0.5 t at spherical support. The finite element model includes MV, GP, CSS, inner vessel, CP, TB and top shield (Fig.9). The core is modelled as an equivalent solid.

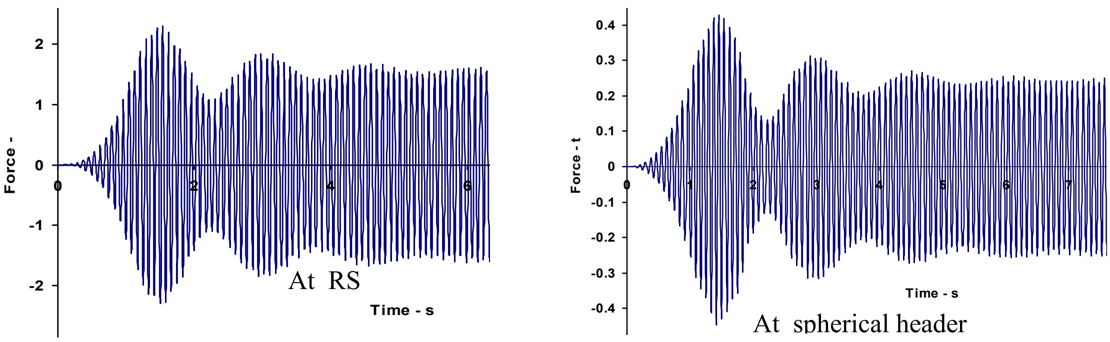

Fig.8 Dynamic forces at the PSP supports

GP, CSS and TS, which are of box type, are replaced by geometrically similar axisymmetric solids with modified elastic modulus and density, so as to have the same natural frequencies. PSP and IHX are not included in the finite element model, as they do not affect the results. Free vibration analysis has indicated that the natural frequency of control plug is ~ 9 Hz which matches with the PSP shaft frequency and hence, from the response analysis results, it is found that CP is experiencing maximum displacement with the maximum amplification of about 7 under its normal operating speed, due to resonance phenomenon (Fig.10). The maximum amplitude of vibration of control plug under pump induced excitation force at the roof slab is estimated to be ~ 450 μ. The order of vibrations for other internals such as inner vessel and TB, are insignificant (<150μ), as seen in Fig.11.

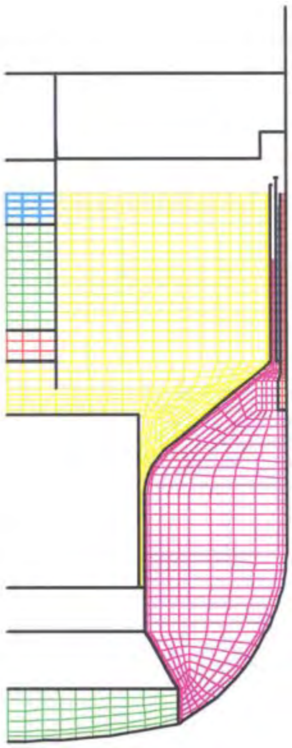

Fig. 9 FE Mesh of RA

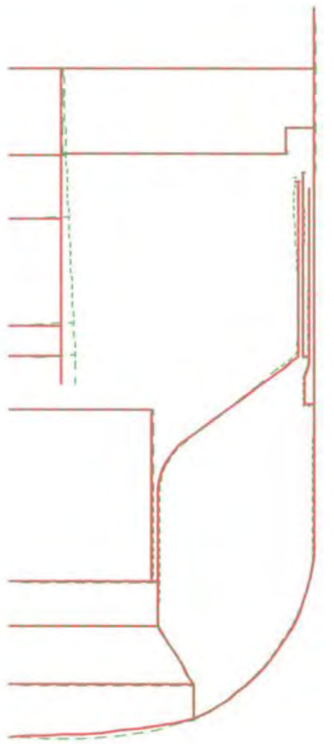

Fig. 10 Dynamic Response of CP

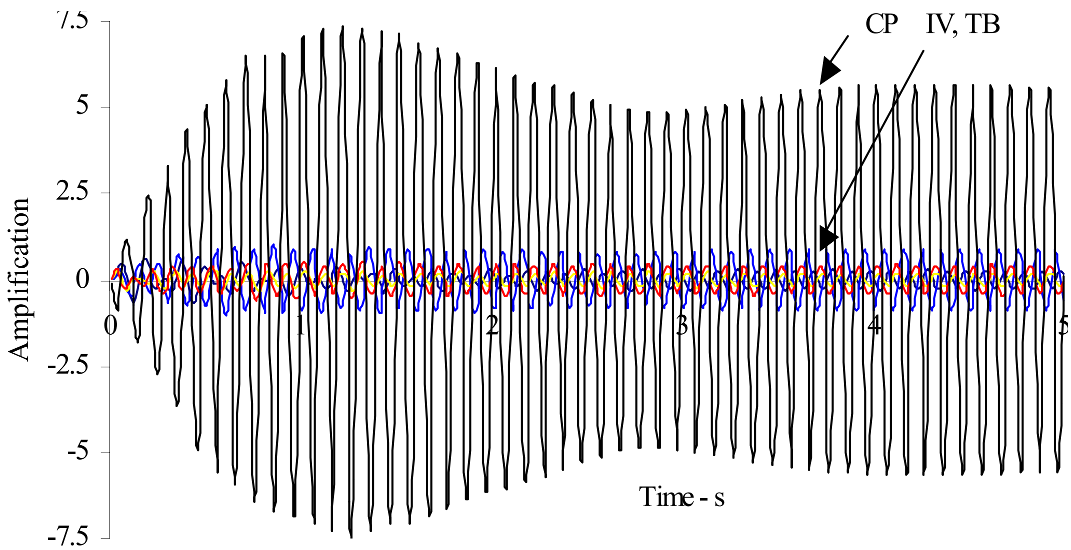

Fig.11 Dynamic response of reactor internals

VIBRATION RESPONSE UNDER FLOW INDUCED EXCITATIONS

Vibration Response of Inner Vessel

The source of vibration of inner vessel is the random pressure fluctuation on the sodium contact surfaces of upper cylindrical shell. The free level fluctuations (± 150 mm) with in the low frequency range (0.5-2 Hz) is another source of vibration. Vibration response of inner vessel is computed using CASTEM 3M for the finite element mesh indicated in Fig.9 using Fourier option, by varying the circumferential wave number (n). The pressure fluctuations due to level oscillation are assumed with varying frequencies. The amplitudes of tip displacement of upper shell with and without incorporating stiffener at the tip of the upper shell, are plotted as shown in Fig.12 which shows that the maximum tip displacements are ± 2.5 mm for the case without stiffener and ± 1.3 mm with stiffener, occuring at n equal to 11 and 9 respectively, due to resonance. Fig.13 shows a typical vibration mode shape. Since, a stiffener has been introduced for PFBR, the vibration amplitude of 1.3 mm which causes very insignificant fluctuating stress (< 2 MPa) is acceptable.

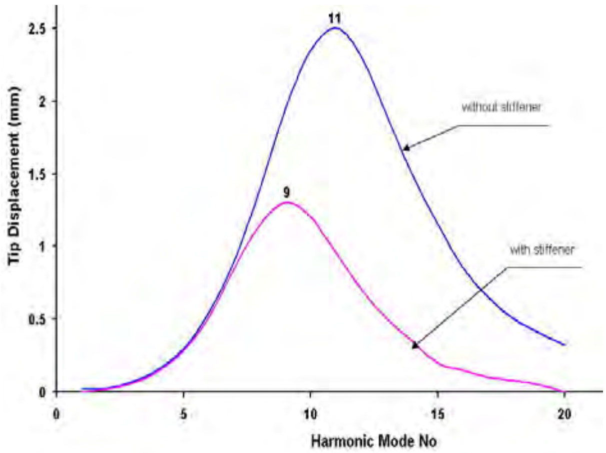

Fig.12 Displacement of inner vessel tip

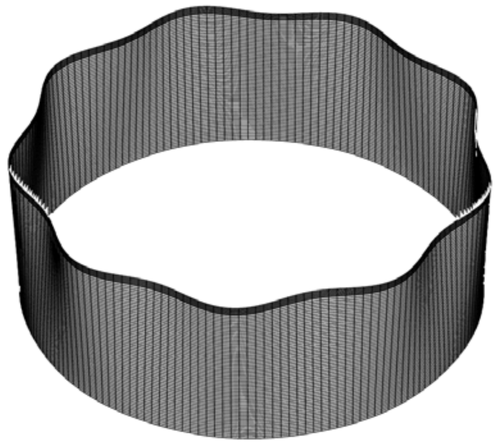

Fig.13 Vibration mode shape of upper shell

Fluidelastic Instability Analysis of Thermal Baffles

The natural frequency analysis indicates that the critical sloshing frequencies are 0.54 Hz (out-of-phase) and 0.55 Hz (in-phase). The corresponding shell frequency is 2.3 Hz. The instability domains are identified using the following instability criteria formulated by Aita [2]:

$\sin\beta - u.\cos\beta > \xi / \Delta\psi$.

where $\beta = \omega_o.\tau$, $u = v/v_o$, $\Delta\psi = (\omega_2-\omega_1)/\omega_o$, ξ is damping ratio, $\omega_o = \sqrt{(g/L)}$, $v_o = \sqrt{(g.L)}$, L is mean radius/circumferential wave number, g is acceleration due to gravity and ω_2 & ω_1 are natural frequencies (rad/s) that are associated with out-of-phase and in-phase sloshing modes. τ and v are the travel time and terminal velocity of liquid flowing from the weir shell crest to the free level of restitution collector, which are determined knowing flow rate and fall height. For the ξ = 1 %, the weir shell is found to be stable under all the operating condition except under fuel handling condition (FHC). The operating point (80 kg/s flow rate and 700 mm fall height) lie in the unstable regime during fuel handling condition (Fig.14).

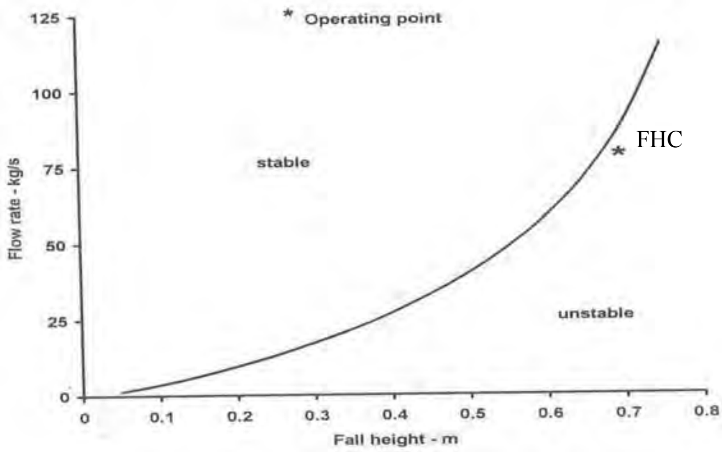

Fig.14 Fluid elastic instability zones for weir shell

Hence detailed nonlinear analysis is carried out to quantify the vibration amplitude. Towards this, self induced fluid forces on the weir shell in the reactor assembly of a typical pool type fast breeder reactor due to sloshing of liquid free levels are identified and analytical expressions are derived. Using the modal super position principles, the modal based non-linear dynamic equilibrium equations are written. Subsequently the equations are solved by direct integration technique using Newmark-β method using the natural frequencies and mode shapes computed numerically through CASTEM 3M code [3]. The evolution of dynamic displacements of weir shell for the ξ = 0.5 % and 1 %, are predicted as depicted in Fig.15. The maximum amplitude of vibration is 3.5 mm for ξ = 0.5 % and negligible for ξ = 1 %. Generally, ξ value for the model is ~ 5 % and for the reactor, it is 1-2 % [4]. Hence, the weir shell vibrations are negligible during fuel handling condition, even though linear instability criteria indicates that it is unstable. This also demonstrates that Aita's instability criteria is conservative.

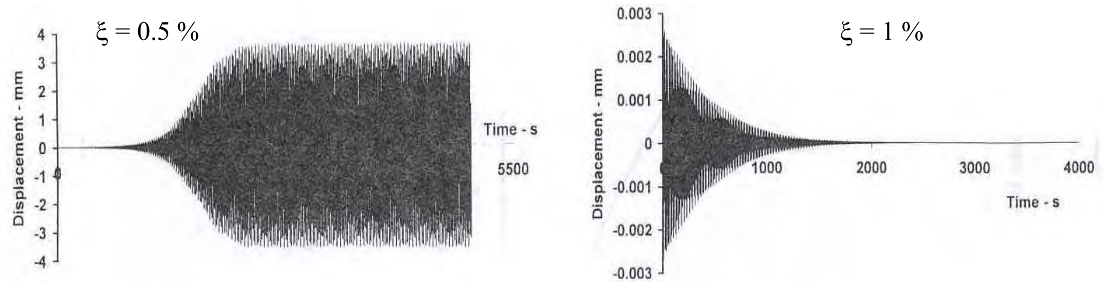

Fig.15 Dynamic response of weir shell

Flow Induced Vibration of CSRDM

The finite element model includes translational tube, GOR, outer sheath and CSR. 2-noded axisymmetric shell elements of CASTEM 3M with Fourier option are used (Fig.16). The sodium inside as well as outside the tubes are accounted as added mass, distributed over the length (mass replaced by the tubes and contained in the tubes). The sodium layer of 7.7 mm thick between hexagonal sheaths of CSR over the length of ~ 1.5 m is modeled with 4-noded fluid elements. Thus, the fluid-structure interaction effects are taken in to account realistically between the sheaths. The joints between GOR and translational tube at two elevations are modeled by applying appropriate constraints on degree of freedom. The fixed boundary conditions are applied at the level of electromagnet for the translational tube and at the control plug top plate elevation for the outer sheath. The bottom point of CSR is constrained to move in radial directions, ignoring the gap of 0.2 mm between bore and bottom coolant passage tube. Further, for the purpose of parametric study, the bottom point is left free for determining very pessimistic results.

The first five natural frequencies are 1.82, 2.12, 6.55, 8.64 and 9.16 Hz respectively with radial constrain at the bottom point of CSR. When there is no constrain, the frequencies are decreased to 1.26, 2.1, 2.86, 7.31, 9.04 and 14.51 Hz respectively. These modes are 'beam type bending modes with fluid coupling'. Thermal hydraulic analysis indicates that about 90 % of the hot sodium, ejecting from core, flows radially in the space between SA top and CP bottom [5]. Because of this, a portion of upper coolant passage tube (~150 mm length) is subjected to a cross flow velocity of ~ 1 m/s (maximum). Corresponding to this velocity and considering the Strouhal number of 0.2 (applicable for the isolated tube), the vortex shedding frequency works out to be 4 Hz. Hence, the first two modes in the restrained case and the first three modes for unrestrained case are the critical modes, by which resonance condition is unavoidable under part load reactor operation.

Subsequently, response analysis is carried out. For this, the lift force developed by vortex shedding per unit length is computed using: $F(t) = C_L \times \rho \times V^2/2 \times D x \sin(2\pi ft)$ N/m. As recommended in ref. [1], a lift coefficient of unity (conservative) and damping of 1.5% are used. The outer diameter D is 50 mm and hence $F(t) = 20x\sin(8\pi t)$. The peak displacements at the CSR tip are computed as shown in Fig.17 for the critical resonance frequency of 2 Hz. Response analysis is repeated for range of frequencies to consider the variations of excitation frequencies under various reactor operations. The peak displacements at CSR tip for the unrestrained case and at the loading point for the constrained case are shown in Fig.18. From the figures, it is clear that the maximum possible radial displacement is 1 mm for the case without restraints. With restraint, the maximum displacement

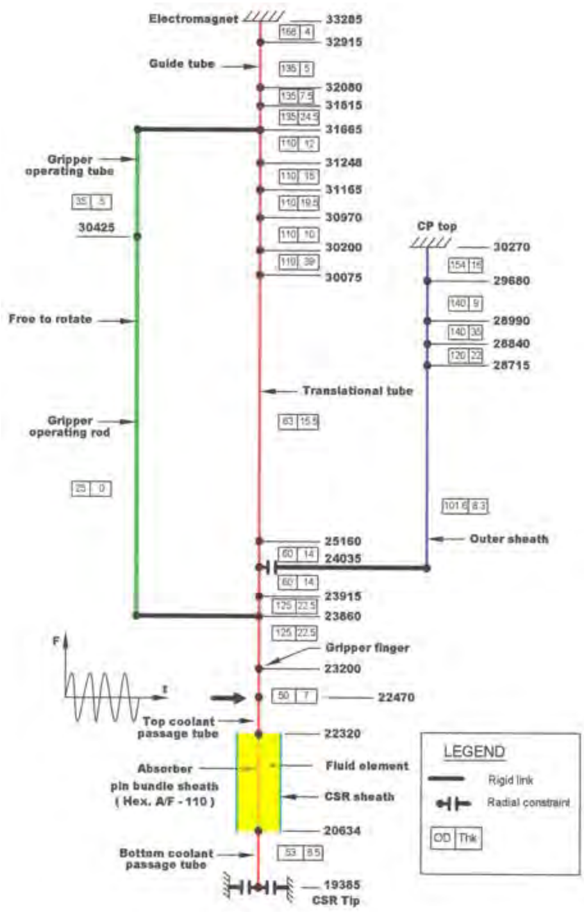

Fig.16 FE Mesh for CSRDM

is limited to 0.5 mm. The peak stress does not exceed 2 MPa which is negligible. Since, the nominal gap between the sheaths is 7.7 mm, mechanical interaction between them is not possible. Hence, there is no fear of FIV risks for CSRDM parts.

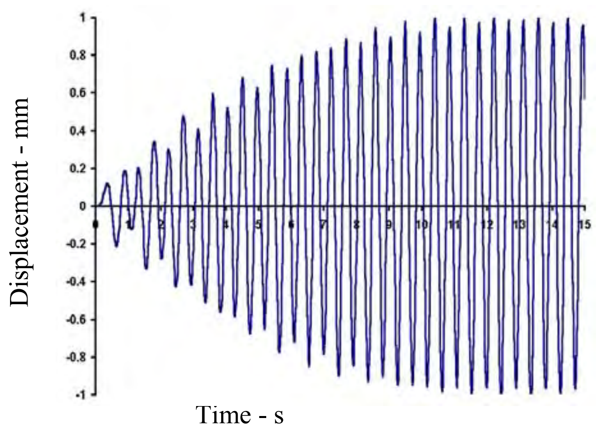

Fig. 17 Vibration response of CSR bottom tip

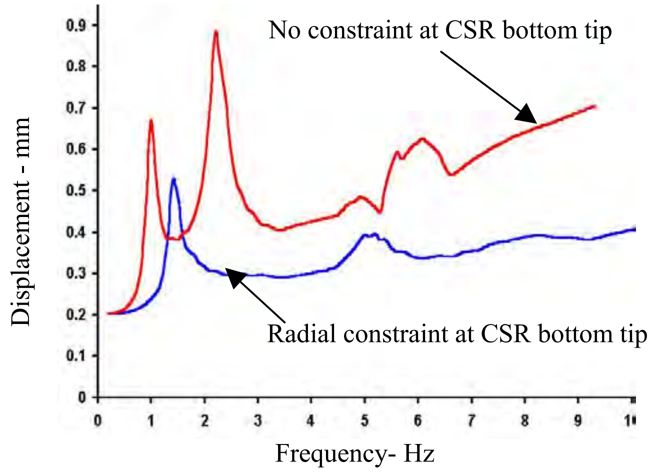

Fig.18 Frequency response of CSRDM

CONCLUSIONS

The vibration responses of PSP as well as dynamic forces at its supports are estimated. For this, the stiffness properties of hydrostatic bearing are determined numerically, by solving governing equations of fluid as well as structures. The vibration amplitude under resonance is ~160 μ which is less than the nominal radial clearance of 400 μ and hence acceptable. The dynamic forces are used as input data for the response of RA components, mainly inner vessel, TB and CP. The CP, natural frequency of which is matching with the pump shaft frequency (9 Hz), is experiencing maximum vibration amplitude of ~ 450 μ. Dynamic response of RA components is also predicted for the pressure fluctuations caused by sodium free level oscillations (±150 mm), under which, the inner vessel is experiencing maximum vibration (± 1.3 mm). Weir shell subjected to fluid forces developed at the associated sodium free levels is analysed and the maximum amplitude of stable vibration of TB is ± 3.5 mm for the damping of 0.5 %. With the realistic damping ratio (1.0 %), the vibration is found to be absent. The CSRDM is analysed for the response under flow induced forces developed due to vortex shedding under cross flow across the top coolant passage tube. The maximum amplitude of vibration is found to be < 1 mm without any restraint at the CSR tip at the bottom. With the restraint for radial motions, it is limited to 0.5 mm. In summary, it is concluded that the reactor assembly internals are free from any risk of mechanical as well as flow induced vibrations.

REFERENCES

1. ASME- Appendix N, Structural Dynamic Analysis, 2001.
2. Aita, S. and Gibert, R.J., "Fluid Elastic Instability in a Flexible Wire: A Theoretical Model", IAEA Specialist meeting on flow induced vibrations in fast breeder reactor, IWGFR-62, Paris – France, October 22-24. 1986.
3. Chellapandi, P., Jaladeen, S., Chetal, S.C. and Bhoje, S.B., " Fluid Elastic Instability of Thin Shells of an FBR", First international conference on vibration engineering and technology of machinery (VETOMAC-1), Indian Institute of Science, Bangalore, Oct 25-27, 2000.
4. Lacroix, C. and Viollet, P.L., "Hydroelastic Study of Instability of Cooling Circuit of Super Phenix", , IAEA Specialist meeting on flow induced vibrations in fast breeder reactor, IWGFR-62, Paris – France, October 22-24. 1986.
5. Natesan., K., et al., "3-D Flow Distribution in a Long Annulus between the Stepped Cylinder and Perforated Shell", Proc. 26th National Conference on Fluid Mechanics and Fluid Power, IIT, Kharagpur, December 13-15, 1999.

* * *