Numerical and Experimental Investigations of Tube-to-Tube Interaction of Air Heat Exchangers of PFBR under Seismic Excitations

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Abstract.

Numerical and experimental investigations of seismic response behaviour of the air heat exchanger (AHX) of prototype fast breeder reactor (PFBR) were carried out for operating basis earthquake (OBE) and safe shutdown earthquake (SSE) conditions. For the numerical study, a finite element model consisting of AHX header and connecting tubes were developed using general purpose finite element code CAST3M and time history analyses were performed for earthquake loading conditions corresponding to OBE and SSE. To perform the analyses, spectrum compatible time histories were generated from the floor response spectrums at the support location of the AHX. Studies predicted the possibility of tube-tube interaction between the middle and outer tubes due to the presence of circumferential fines provided along the tube length. To confirm the analyses findings, shake table experiments were performed using 100 t multi axial shake table. The test set up consists of five AHX tubes along with fines arranged in triangular pitch with tube to tube spacing same as the AHX in the reactor. The tubes were supported simulating the actual supporting conditions in the reactor. To simulate the fluid effects under dynamic conditions, tubes were filled with water and pressurized up to 5 bars. Prior to the seismic studies, free vibration characteristics of the tube bundle were estimated by performing resonance search tests and compared the results obtained from tests with numerical predictions. The responses were captured using accelerometers, strain gauges and non contact type displacement sensors. Tube responses are assessed for OBE and SSE conditions by performing the tri axial excitations as per IEEE-344 guidelines using spectrum compatible time histories and responses are captured using a 96 channel data acquisition system. Tube to tube interactions at fin locations were observed under OBE and SSE conditions as evidenced from the response spikes in accelerometer and strain gauge readings and from the relative displacements measured using non contact type displacement sensors. However, the structural integrity of tube bundle is demonstrated by repeating the experiments many times for OBE and SSE conditions. From these experiments, it is confirmed that, the local impacts at the fin locations are not a concern for the structural integrity of AHX.

Key Words: SFGDHR, AHX, OBE, SSE

1. Introduction

Safety grade decay heat removal (SGDHR) system in PFBR is a passive decay heat removal system which works on the principle of natural circulation of sodium between two thermal centres kept at different elevation in the reactor. SGDHR system works on the principle of natural circulation of sodium created by placing the thermal centres (inlet and outlet) at different elevations which creates the density difference which is the driving force for the natural circulation. Sodium to Air heat exchangers (AHX) are the integral part of safety grade decay heat removal (SGDHR) system, which removes the decay heat from primary sodium to atmospheric air there by keeping the primary sodium pool temperature below acceptable limit. There are four independent SGDHR loops in PFBR, each with 8 MW heat removal capacity. For achieving diversity in the design, two loops out of four SGDHR loops are having AHX of type-A and, other two loops are having AHX of type-B. Any rupture in the header or tubes of AHX results leakage of sodium into atmosphere causing sodium fire, impairing the operation of the SGDHR system. Hence the integrity of the AHX has to be ensured in all categories of events which impart various loading conditions on AHX. Among various design basis events, earthquake excitations generate the highest mechanical loading in the AHX which is dynamic in nature. Type-A AHX consists of rigid inlet and outlet headers which are connected by a series of finned tubes of thickness 3 mm. The tubes are placed in triangular pitch with a centre to centre distance of 87.8 mm with large span between intermediate supports. Major portion of these tubes are fitted with fines of height 12.5 mm reducing the effective gap between the inner and outer tubes in the finned region to 24.7 mm. In case of an earthquake, tube to tube interaction may occur if the relative displacements are more than the effective gap between the tubes. Hence it must be ensured that, these tube to tube interactions at the finned region will not cause any rupture of AHX tubes in the event of a seismic excitation corresponding to OBE or SSE. To verify the possibility of tube to tube interaction, time history analyses have been performed and to confirm the analysis results and to demonstrate the structural integrity of these tubes, shake table experiments were performed on 100t shake table for OBE and SSE conditions. Five tubes maintaining the designed centre to centre distance of the tubes have been used for analysis and experiments. The tube array configuration selected for the experimental study was selected in such a way that it completely captures all the aspects of tube to tube interaction during seismic events.

2. System Description

PFBR have four SGDHR circuit each with 8 MW heat removal capacities. Each loop consists of decay heat exchanger (DHX), Air heat exchanger (AHX), expansion tank, and storage tank and associated piping systems. DHX exchange the decay heat in the primary sodium to the sodium in the SGDHR system. SGDHR system carries the hot sodium from DHX to the AHX which are connected through the piping system. AHX transfers this heat to atmospheric air passing through shell side of AHX and cold sodium returns back to the DHX through the return piping completing the heat transfer loop. Schematic figure of SGDHR system is shown in fig.1. Out of four SGDHR loops, two loops are with DHX and AHX of type-A design, and other two loops are with DHX and AHX of type-B design to achieve the diversity in design. Steam generator building-1 (SGB1) contains 2 SGDHR loops, one of Type-A and other of Type-B and Steam generator building-2 (SGB2) contains 2 SGDHR loops, one of Type-A and other of Type-B. Each loop is of 8 MW heat removal capacities and out of four loops three loops are sufficient to remove the decay heat generated in the reactor. AHX are located at elevation 60 m of SGB. It is a cross flow type heat exchanger. Sodium is flowing through the tubes and air is flowing over the finned tube. In AHX-A, the inlet and outlet headers are connected by serpentine type tubes with fines as shown in fig.2. AHX-B is a vertical cross flow type heat exchanger where the ring type inlet and outlet headers are connected by straight finned tubes. For diversity in AHX, different fin type, fin height, number of fins per inch and tube bundle arrangement is adopted. In AHX- A, solid fin of 12.5 mm fin height and 5 fins/in and serpentine type horizontal tube bundle is used. In Type B serrated fin of 19 mm fin height and 6 fins/in and straight vertical tube bundles is used.

3. Seismic Qualification of AHX

Since SGHDR system is classified as safety class-1 and seismic category-1 structure, all the components of SGDHR such as DHX, expansion tank, AHX, storage tank and associated piping systems have to be qualified for normal as well as seismic loading conditions corresponding to OBE and SSE. Response spectrum method is adopted for seismic qualification of components of SGDHR system. Seismic analyses indicated that the stresses are within allowable limits for all the components. But the analysis predicted the possibility of tube to tube interactions in AHX tubes which was more predominate in AHX-A tubes due to its tube layout and support configuration.

4. Analysis for Assessment of Tube to Tube Interaction in AHX-A

AHX (Type-A) is serpentine cross flow type heat exchanger with finned tubes. This has horizontal sodium inlet (top header) and outlet (bottom header) headers, which are connected by 116 tubes arranged in three longitudinal and 77 transverse rows. Each tube is arranged in a serpentine layout with four passes in AHX. There are three un-finned U tube bends, making the serpentine layout for each tube. Finned tubes, U-bends and sodium headers are all housed inside a single casing of AHX as shown in fig.2. AHX (Type-A) has been modeled and seismic analysis has been performed for the OBE as well SSE excitations using spectrum compatible time histories which generated from the spectra enveloping the support locations of AHX. The details of the analysis are described below.

4.1 Model and Material Descriptions

AHX-A headers and tubes are modelled as 3D equivalent beam elements using finite element code CAST3M as shown in fig.3. The model consists of inlet and outlet headers and 116 tubes. The boundary conditions for the model are described in fig.4. Sectional properties of the tubes are modified in the finned region to simulate the added stiffness and mass of the fins. The stiffness properties of finned tubes are obtained from the 3D model used for the thermal analysis of the AHX tubes [1] by applying forces at respective degrees of freedom and calculating the deflections. There are three different types of tubes connecting headers. They differ in the bend configurations and the straight region with fins remains identical for all these configurations. In the straight region of the tubes the fins are helically wound over the tubes. Tubes and headers are made of 9 Cr 1 Mo materials with inlet header temperature as 819 K and outlet header temperature as 795 K. Average tube temperatures is taken as 807 K. Material properties of corresponding to these temperatures are used for the analysis. Tubes in AHX-A are arranged in a triangular pitch as shown in fig.5.

4.2 Modal and Response Spectrum Analyses of AHX

Free vibration analysis has been performed for AHX-A to obtain the dynamic characteristic of AHX-A such as natural frequencies, mode shapes and mass participation etc. Fundamental vibration mode of AHX is 5.1 Hz which is in-plane bending of inner row of tubes. Nearby modes of 5.13 Hz and 5.18 Hz show the in plane bending of outer row of tubes and middle row of tubes respectively. The difference n natural frequencies are attributed to the different configurations of these tubes. Fundamental frequencies of the top header and bottom header are 58.9 Hz and 94.3 Hz which implies that the headers are very rigid compared to the tube. Fig.6 depicts the predominant modes for AHX-A tubes. Subsequent to natural frequency analysis, response spectrum analysis has been carried out for AHX for OBE and SSE conditions. Response spectra enveloping the floor response spectra at the support locations of AHX headers and tubes are used for the analyses. For OBE analysis, spectra corresponding to 2% damping (fig.7) and for SSE, spectra corresponding to 4 % damping (fig.8) are used for the analyses [2]. Analyses results indicated the possibility of tube to tube interaction of middle tube with outer and inner tube by considering the reduced gap in the fin region due to the presence of fins. The stresses are found to be within the acceptable limit neglecting the possible tube to tube interactions. Since response spectrum method lacks the phase information of the relative movement between the tubes, possibility of the tube interaction were predicted with conservative estimate. So to establish the possibility of the tube to tube interactions modal time history analyses has been carried out as described in the subsequent paragraph.

4.3 Time history Analyses of AHX-Tubes

To perform modal based time history analysis of AHX, a reduced model of AHX-A consisting of 5 tubes (two outer tubes, two inner tubes and one middle tube is used, based on the results from the response spectrum analysis viz (i) both headers are rigid and will not alter the tube excitation and can be decoupled (ii) interaction occurs between middle tube with outer and inner tubes and no outer to outer, outer to inner or inner to inner tube interaction is possible due large gap. Fixed boundary conditions are applied to simulate the header to tube connection. Since the intermediate supports of the tube bundles allow axial expansion of the tubes, lateral constraints (axial motion free) are applied to simulate tube intermediate supports. Spectrum compatible time histories are generated such that spectra generated from the simulated time histories envelope the corresponding target envelope spectra for OBE and SSE cases respectively. Fig.9 shows the matching of response spectra and simulated time histories for OBE case. Analysis for OBE and SSE confirmed the possibility of tube to tube interaction which is checked by finding the relative displacements between outer and inner tubes with the middle tube. The possible interaction location is found to be the finned region of the tube which is the region between the two intermediate supports as shown in fig.10.

5. Shake Table Experiments

To confirm the analysis findings and to assess the effect of tube to tube interaction on the structural integrity of the AHX tubes, shake table experiments were performed for the prototype model of the AHX-A tubes using 100 t multi axial shake table available at IGCAR Kalpakkam. The test set up consists of straight portion of the tubes between the intermediate supports with fins as the interaction is predicted in the finned region between the middle supports. Two outer tubes, two inner tubes and one middle tube are arranged in a triangulated pitch between two supports simulating the actual tube layout and the middle support in AHX-A as shown in fig.11. The end supports exactly simulates the intermediate support of the AHX tubes. The test setup is oriented on the shake table such that the direction of excitation matches with the excitation direction in the reactor. The location of various sensors such as accelerometers, strain gauges and laser sensors used for capturing the dynamic responses of the tube during seismic excitations are show in figure 12a and 12b. Test set up is mounted on 100 t shake table with the base plate bolted to the shake table platform as shown in fig.11. Outer tubes are filled with water and pressurized to 5 bar using compressor and locked using valve arrangement. Central tube is filled with lead shot to get slightly different frequency to have out of phase movement between inner and outer tubes. Pressure gauge is mounted to one of the tubes to monitor the pressure variation before during and after the shake table experiments. These tests were conducted as per the recommended practice for seismic qualification of class 1E equipment for Nuclear Power Generating Station, IEEE STD 344-2013: IEEE [2].

Sine sweep tests were conducted prior to the earthquake tests to estimate the natural frequencies of the tube assembly. Fast Fourier Transform (FFT) of the response acceleration for upper middle and lower tubes are shown in fig.13. Shake table experiments were conducted using the spectrum compatible time histories such that test response spectra (TRS) envelops the required response spectra. Responses were measured using accelerometers, strain gauges and laser sensors. Pressure in the attached pressure gauge was monitored before, during and after the tests for OBE and SSE cases. Samples are captured using sampling rate of 2000 samples/s from all the sensors. Multiple impacts were observed to occur between fins of middle tube with fins of outer and inner tubes. The visual observations were corroborated by the accelerometer, stain gauge and laser readings for OBE and SSE tests. Fig.14 and 15 show the response accelerations of outer tube and middle tube in lateral direction for OBE and SSE conditions respectively and fig.16 and fig.17 show the strain gauge readings for the respective load cases for OBE and SSE for outer and middle tubes. Strain readings indicate that, the stresses developed in the tubes by impulse loading due to local impacts are lower than the allowable limit indicating that the tubes are safe even with multiple impacts occurs at the fin region. This even true even if we transform these strains to the operating temperature by appropriately with the modulus ratio. Displacement responses of outer, middle and inner tubes are shown in fig.18 and 19 for OBE and SSE conditions respectively. By using horizontal and vertical displacement responses, the orbit plots has been constructed for outer tubes (tube-1 and tube-2) and shown in Figs. 20 and 21 respectively for OBE and SSE. From these orbit plots, it is clear that outer tubes are interacting with middle tube. It was observed that even though multiple impacts were occurring between the fins of middle tube with outer and inner tubes there was no leakage or drop in pressure and no visible dents or impact marks were observed even after repeating the tests giving confidence in the structural integrity of AHX tubes.

6. Conclusion

Dynamic response assessment of AHX tubes under seismic loading conditions were assessed by seismic analysis and shake table experiments on 100 t multi axial earthquake simulator. Analyses and experiments were performed for OBE and SSE conditions. Time history analyses indicated the possibility of interaction of middle tube with outer and inner tubes in the fined region. Experiments were conducted to confirm the analyses findings and to check the effect of tube to tube interaction on the structural integrity of AHX tubes. Test setup consists of five finned tubes which are arranged in the triangular pitch simulating the actual tube layout in the straight portion between the intermediate supports in AHX. Tube responses were captured using dynamic sensors such as accelerometers strain gauges and laser sensors. Series of impacts were observed between middle tube, and the outer tubes. The response peaks in accelerometer and strain gauge readings corroborate the multiple impacts between inner tubes and outer tubes at the fin locations. Even though fin to fin interaction are occurring between the tubes, there was no visible damage or dents observed on the fins or on the tubes even after repeating the experiments many times for both OBE and SSE. These experiments demonstrate that tube to tube interactions at the finned region are not a concern for the structural integrity of the AHX.

7. References

[1] S Jalaldeen, Stress analysis of AHX (type-A) tubes, PFBR/34160/1009/R-A internal Note,2003

[2] R. Balaji, et al, "Floor response spectra generation for NIB-Vol-2" PFBR/20000/DR/2009/R-1, 2008.

[3] IEEE Std.344-2013: IEEE Recommended practice for the seismic qualification of class 1E equipment for Nuclear Power generating station, 2013

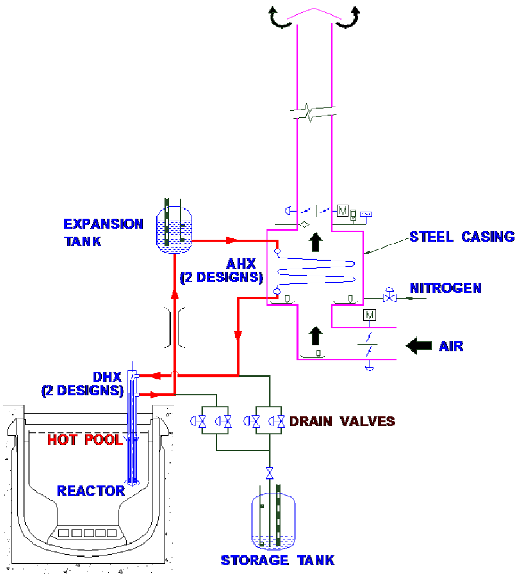


FIG.1 Schematic of SGDHR system

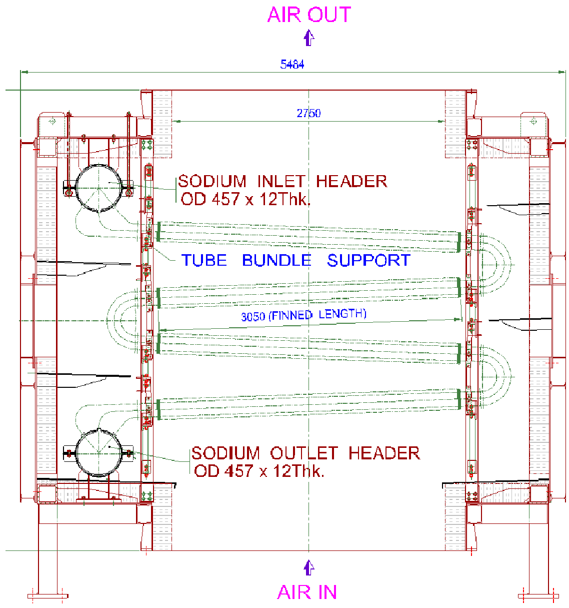


FIG.2 Schematic of AHX-A

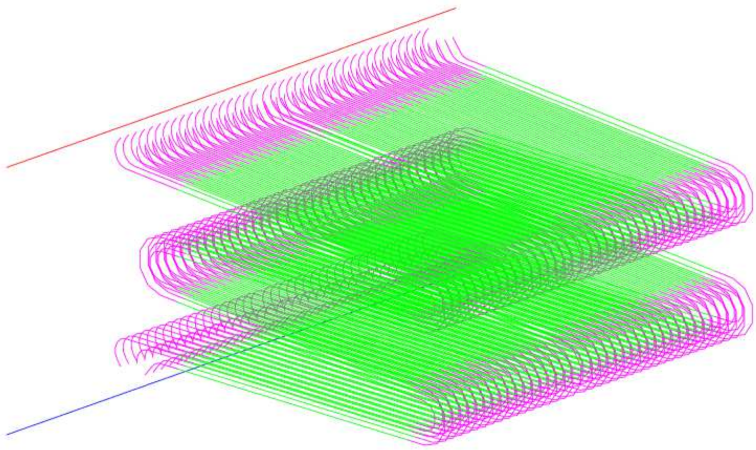


FIG.3 Finite element model of AHX-A

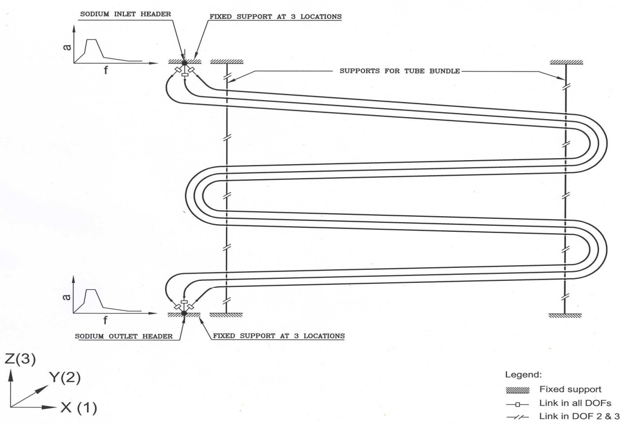


FIG.4 Boundary conditions for AHX-A

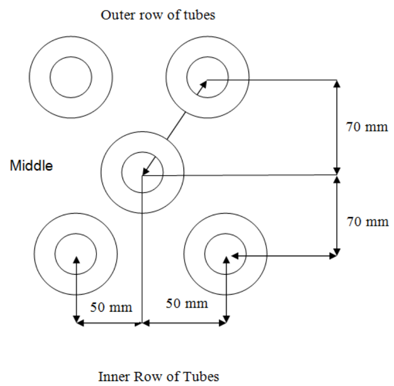
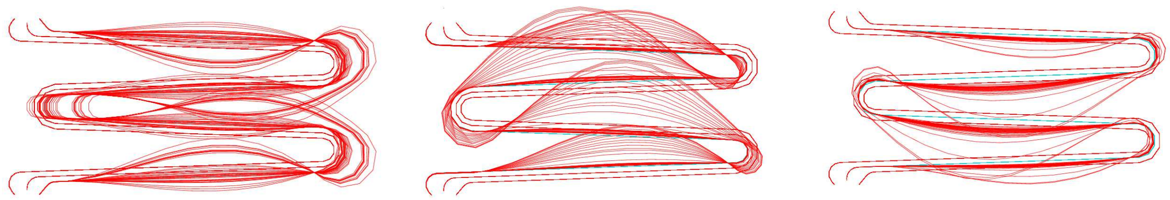
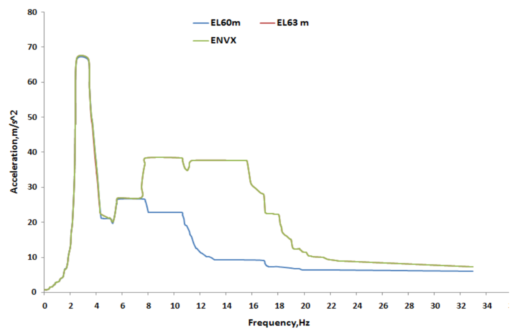


FIG.5 Arrangement of inner outer and middle tubes in AHX-A

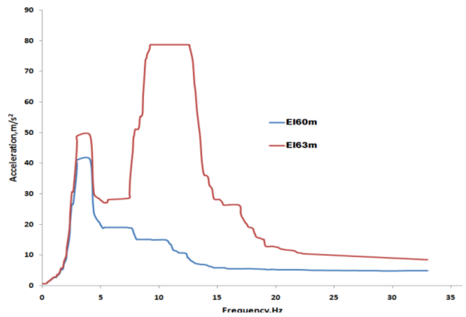


Mode-1 5.1 Hz (inner tube) Mode-1 5.13 Hz (outer tube) Mode-1 5.18 Hz (middle tube)

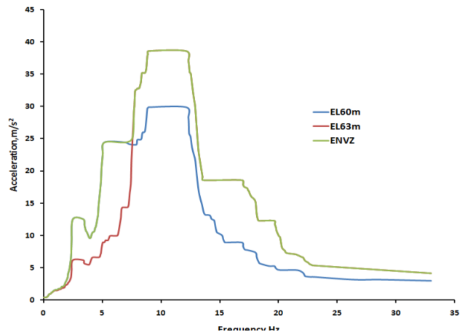
FIG.6 Dominant modes for AHX tubes



(a) X direction

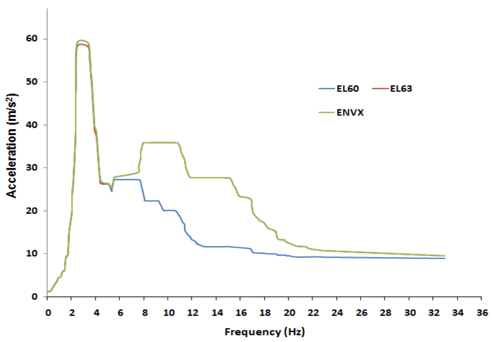


(b) Y direction

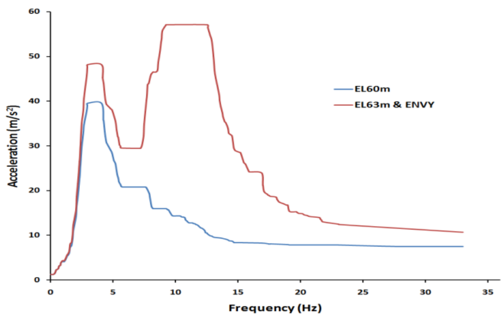


(c) Z direction

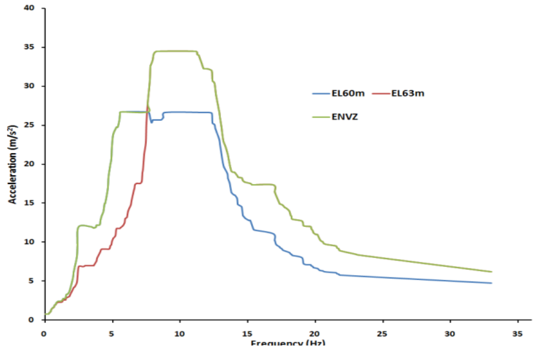
FIG.7 Envelope response spectra for AHX (OBE 2% damping)



(a) X direction

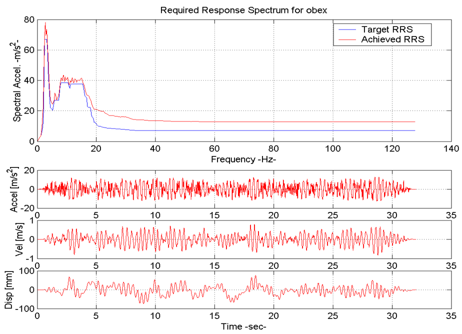


(b) Y direction

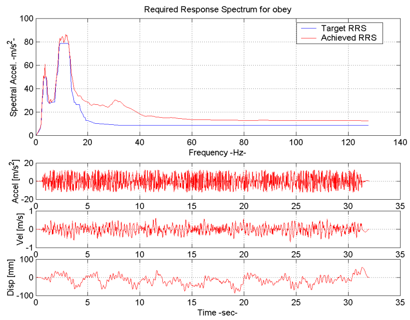


(c) Z direction

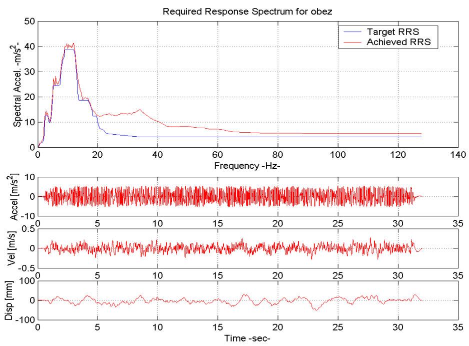
FIG.8 Envelope response spectra for AHX (SSE 2% damping)



(a) X direction



(b) Y direction



(c) Z direction

FIG.9 Generation of Spectrum compatible time histories (OBE)

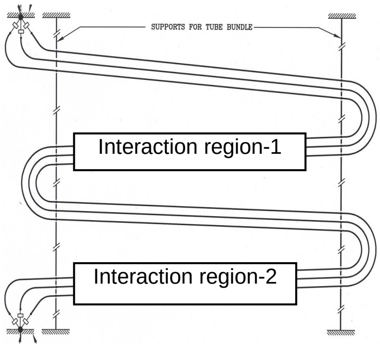


FIG. 10 Region of possible interaction

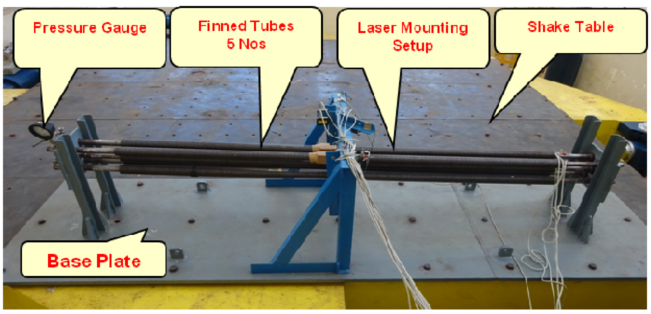
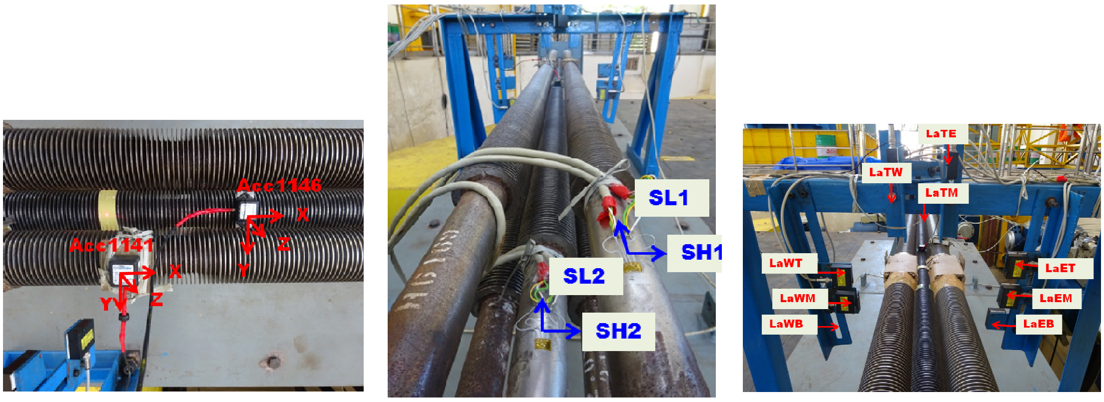
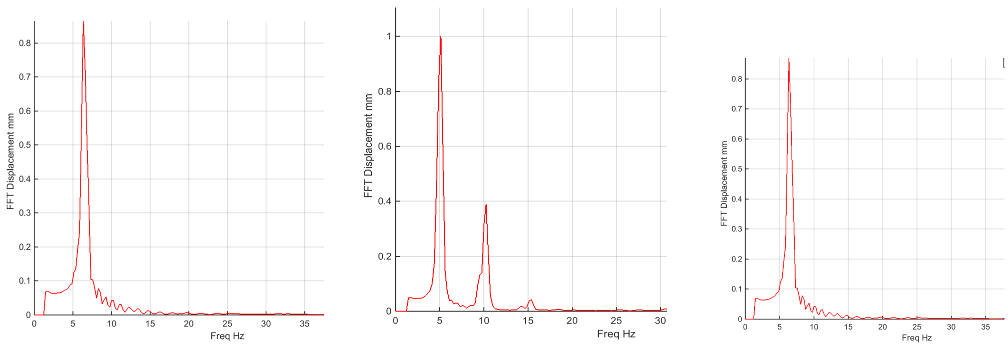


Fig.11 Test specimen on shake table



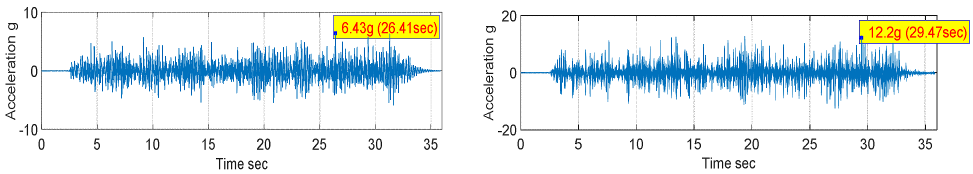
(a) (b) (c)

FIG.12 Location of various sensors; (a) accelerometers; (b) strain gauges; (c)Laser sensors



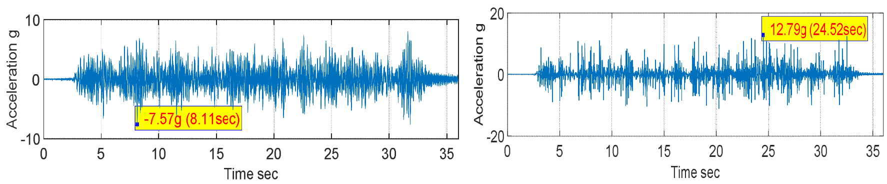
(a) (b) (c)

FIG.13 FFT response for frequency sweep tests; (a) outer tube; (b)middle tube;(c)inner tube



(a) (b)

FIG.14 Acceleration response for OBE; (a)outer tube;(b)middle tube



(a) (b)

FIG.15 Acceleration response for SSE; (a) outer tube;(b)middle tube

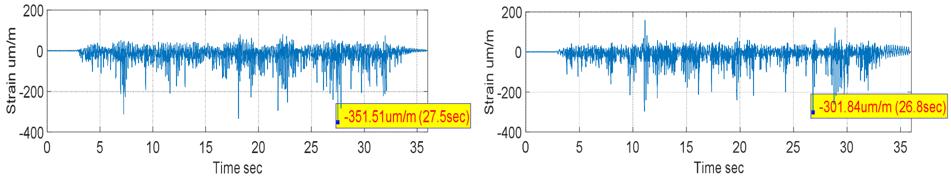


FIG.16 Strain response for OBE; (a) outer tube;(b)middle tube

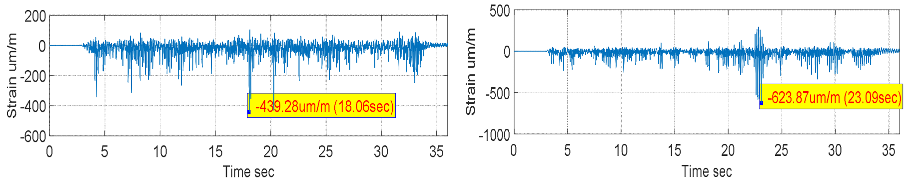
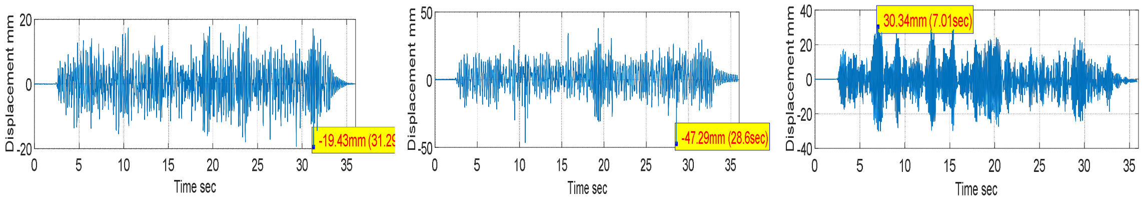


FIG.17 Strain response for SSE; (a) outer tube; (b) middle tube



(a) (b) (c)

FIG.18 Displacement response for OBE; (a) outer tube; (b) middle tube; (c)Inner tube

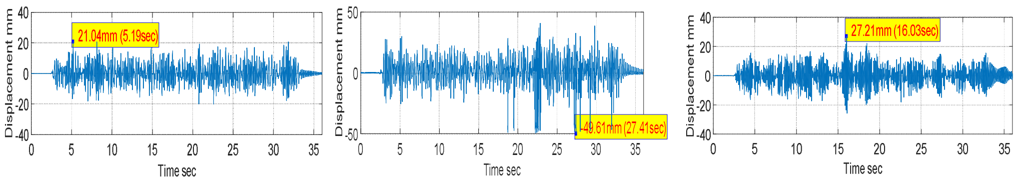
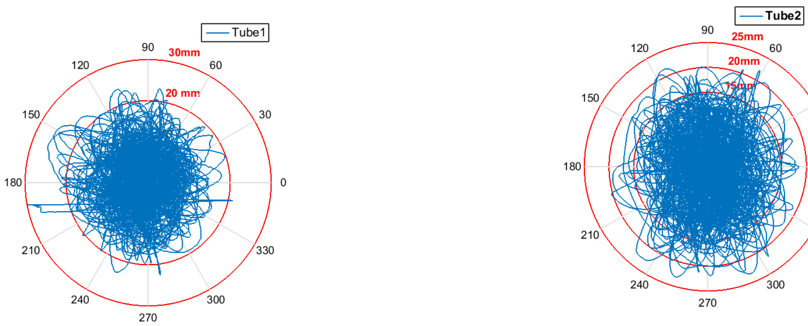


FIG.19 Displacement response for SSE; (a) outer tube; (b) middle tube; (c) Inner tube



(a) (b)

FIG.20 orbit plots for outer tubes for OBE; (a) Outer tube-1; (b) Outer tube-2