Modal Measurements on PFBR Steam Generator Tubes


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ABSTRACT: Modal characteristics of tube support system of 500 Mw(e) Prototype Fast Breeder Reactor Steam Generator were measured on a three tube model. Impulse excitation was used and natural frequencies and mode shapes were obtained using transfer function method. Experiments were carried out with different tube support conditions. Measured modal parameters were found to be in good agreement with theoretically predicted values and the experimental results also confirmed the effectiveness of the two closely spaced anti-vibration belt supports at both ends of the bend.

1.0 INTRODUCTION

The proposed 500 MWe Prototype Fast Breeder Reactor (PFBR) at Kalpakkam is a liquid metal sodium cooled reactor. The steam generator is a vertical shell and tube heat exchanger with sodium on its shell side and water in tube side. The tubes have an expansion bend to take care of thermal expansion and they see cross flow at inlet, expansion bend and outlet locations. One of the initiating causes for tube failure is the tube vibration caused by sodium flow. A three tube model was designed and assembled for studying the modal parameters of the tube and to familiarise with the behavior of the tube support system. Modal characteristics were obtained using impact hammer method and assumptions made in the tube support conditions were verified. The effectiveness of two closely spaced anti-vibration supports at either end of the bend in the stem generator was confirmed. Subsequent to the modal measurements on the three tube model, flow induced vibration(FIV) measurements were carried out on a 60° sector model. The vibration level measured in the bend region was found insignificant and hence showed the adequacy of tube support system provided at the bend region. The tube vibration characteristics observed in the other spans of the sector model were also in good agreement with modal measurement results of three tube model.

2.0 MODEL DESCRIPTION

Fig-1 schematically illustrates the details of three tube model of the PFBR steam generator. The support conditions at tube sheet (rolled joint) and the intermediate support at anti-vibration
belt locations were maintained in the three tube model similar to the prototype unit. The model tube length was made shorter by reducing the number of straight spans on either side of the bend. The three tube model is the smallest configuration, in which the support conditions can be well simulated. The measurements were carried out in air.

3.0 MEASUREMENT PROCEDURE

An impact hammer was used for exciting the tubes and response of the tubes was measured using piezoelectric accelerometers. The accelerometer was fixed in one of the spans 4, 7 or 6 (bend) and the tube was impacted at a number of points along its length using impact hammer with rubber tip. The outputs from the accelerometer and the force transducer, which forms part of the impact hammer, were fed to FFT analyzer to obtain the transfer function. At resonance the real part (cosine) of the transfer function becomes zero and the imaginary part (sine) becomes peak. Mode shape is obtained by plotting the value of imaginary part of the transfer function obtained at various points of impact.

Measurement of Out-of-plane and In-plane modal characteristics of tube were carried out with a) all supports effective and b) with two supports (support no-5 and 6) near the bend ineffective.

4.0 RESULTS AND DISCUSSION

Table-1 & 2 show the predicted (SAP4 & PAFEC) and measured values of modal frequencies of tube support system. Fig-2 shows the measured mode shapes. There is good agreement between measured and predicted values of modal frequencies and mode shapes. Hence the assumptions made in the theoretical predictions on the boundary conditions at support locations were correct and anti-vibration belts act as pinned support. In the bend portion, both experimental and analytical results indicate that the maximum vibration response occurs approximately mid-way between the bend center support No-10 and support No-5.

<table>
<thead>
<tr>
<th>Software</th>
<th>Inlet region</th>
<th>Bend region</th>
<th>Outlet region</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAFEC</td>
<td>33.4</td>
<td>71.4 (IP)</td>
<td>41.9</td>
</tr>
<tr>
<td></td>
<td>47.9</td>
<td>99.3 (OP)</td>
<td>58.0</td>
</tr>
<tr>
<td></td>
<td>57.0</td>
<td></td>
<td>79.0</td>
</tr>
<tr>
<td></td>
<td>75.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAP4</td>
<td>32.0</td>
<td>65.4 (IP)</td>
<td>40.3</td>
</tr>
<tr>
<td></td>
<td>46.4</td>
<td>78.9 (OP)</td>
<td>55.7</td>
</tr>
<tr>
<td></td>
<td>55.1</td>
<td></td>
<td>74.2</td>
</tr>
<tr>
<td></td>
<td>74.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IP - In plane  OP- Out of plane
Table II Natural Frequencies - Experimental Values (Hz)  
(Out-of-plane)

<table>
<thead>
<tr>
<th>Tube</th>
<th>Inlet region</th>
<th>Bend region</th>
<th>Outlet region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Tube</td>
<td>30.4, 34.4</td>
<td>72.8, 87.2</td>
<td>37.6, 55.2</td>
</tr>
<tr>
<td></td>
<td>46.4, 56.0</td>
<td>98.4</td>
<td>74.4</td>
</tr>
<tr>
<td></td>
<td>74.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle Tube</td>
<td>30.4, 36.0, 48.8</td>
<td>72.8, 87.2</td>
<td>41.6, 56.0</td>
</tr>
<tr>
<td></td>
<td>56.0, 74.4</td>
<td>98.4</td>
<td>74.4</td>
</tr>
</tbody>
</table>

The experimental mode shapes confirmed that the three "regions" classified in the Table I vibrate independently at different modal frequencies and there is isolation between them. At both ends of the bend, two antivibration belts are provided close to each other. The arrangement seems to isolate the three regions and also the lowest out of plane natural frequency of the bend region is considerably increased.

Fig-3a shows the transfer function obtained, with the accelerometer mounted on the bend region and the excitation given at the same bend. The three frequency peaks seen in the figure correspond to the modal frequencies of the bend region as shown in Table-I & II. When impact was given at the inlet region (fourth span), none of the modal frequencies were excited in bend region as shown in Fig-3b. This confirms the isolation between the three regions.

In order to further confirm this, supports closest to the bend on either end (support No-5 & 6) were removed and modal frequencies were determined experimentally. It was observed that the entire length of the tube acts as a continuous beam in this case. The lowest modal frequency of 30.4 Hz was also excited in the bend region as shown in the Fig-4 and this is much less than 72.8 Hz in the bend region when all supports are effective. Since a higher modal frequency is desirable in the bend region from cross flow induced vibration consideration, the need for two closely spaced supports at either end of the bend in the prototype steam generator was confirmed from these measurements.

5.0 FIV EXPERIMENTS ON 60 DEGREE SECTOR MODEL

Subsequent to the modal measurements on the three tube model, flow induced vibration (FIV) measurements were carried out on a 60° sector model with 45 tubes, in a water test loop[1]. Fig-5 shows the details of the model. The vibration level measured in the tube bend region was 7.5 micron (RMS) at 100% flow (365 Cu.m/h) as shown in Fig-6 and this was found to be very small compared to permissible limit and also shows the adequacy of tube supports provided at the bend region. The tube vibration characteristics in the sector model were also in good agreement with modal analysis results of three tube model.
6.0 CONCLUSIONS

Results obtained from modal measurement on three tube model and FIV measurements on sector model were discussed in this paper. Modal measurement results confirmed that the effectiveness of the two antivibration belts provided close to each other at both ends of the bend region in isolating the three regions of the tube and in increasing the lowest modal frequency in the bend region. FIV measurements have indicated very low vibration levels in the bend region and other spans.

7.0 REFERENCES

AVB = ANTI-VIBRATION BELT SUPPORT

Fig. 1. STEAM GENERATOR THREE TUBE MODEL.
Fig. 2: MODE SHAPES OF S G TUBE WITH ACCELEROMETER IN THREE DIFFERENT LOCATIONS. (TOP TUBE - OUT OF PLANE EXPERIMENT RESULTS)
Impact at bend region.
Accelerometer in bend region.
Fig-3a.

Impact at inlet region.
Accelerometer in bend region.
Fig-3b.

Impact at bend region.
Accelerometer in bend region.
Fig-4.

TRANSFER FUNCTION PLOTS
(IMAGINARY PART)
Fig. 5 PFBR-SG 60 deg. sector model for FIV experiments.

Fig. 6 Overall tube vibration with flow rate