Hindawi Publishing Corporation
Science and Technology of Nuclear Installations
Volume 2008, Article ID 764301, 7 pages
doi:10.1155/2008/764301

Review Article

Dynamic Analysis of Coolant Channel and Its Internals of Indian 540 MWe PHWR Reactor

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Received 13 April 2007; Revised 1 August 2007; Accepted 16 December 2007

Recommended by Juan Ferreri

The horizontal coolant channel is one of the important parts of primary heat transport system in PHWR type of reactors. There are in all 392 channels in the core of Indian 540 MWe reactor. Each channel houses 13 natural uranium fuel bundles and shielding and sealing plugs one each on either side of the channel. The heavy water coolant flows through the coolant channel and carries the nuclear heat to outside the core for steam generation and power production in the turbo-generator. India has commissioned one 540 MWe PHWR reactor in September 2005 and another similar unit will be going into operation very shortly. For a complete dynamic study of the channel and its internals under the influence of high coolant flow, experimental and modeling studies have been carried out. A good correlation has been achieved between the results of experimental and analytical models. The operating life of a typical coolant channel typically ranges from 10 to 15 full-power years. Towards the end of its operating life, its health monitoring becomes an important activity. Vibration diagnosis plays an important role as a tool for life management of coolant. Through the study of dynamic characteristics of the coolant channel under simulated loading condition, an attempt has been made to develop a diagnostics to monitor the health of the coolant channel over its operating life. A study has been also carried out to characterize the fuel vibration under different flow condition.

1. INTRODUCTION

In the first phase of the Indian nuclear power programme, the focus was to construct series of pressurized heavy water reactors (PHWRs) of 235 MWe and 500 MWe ratings in different part of the country. Presently there are 12 PHWRs of 235 MWe in operation and additional four units of similar capacity are under advanced stage of construction. Backed with excellent experience of design, construction, and operation of 235 MWe type reactors, India has stepped onto indigenous design of 540 MWe reactors. The first unit of 540 MWe reactors went into operation successful in September 2005. There are many innovative and evolutionary design features implemented in almost all the systems so as to enhance safety in operation, to extend the useful life of the plant, and to make the operation more users friendly. One such component with new design features is the coolant channel. It forms an important part of primary heat transport system. There are 392 coolant channels in the core mounted horizontally through the calandria and end shield. Each channel carries 13 fuel bundles in the center, one fuel locator, one shielding plug, and one sealing plug on the either ends. The fuel bundle is made of 37 cylindrical fuel elements of 13.22 mm diameter and 495 mm in length. These are held by two end plates to which the elements are spot-welded. The pressurized heavy water coolant flows through the coolant channel to carry the nuclear heat to the steam generators.

The coolant channel and its internals are under constant vibration due to internal coolant flow and the external moderator circulation. In order to qualify the design of the coolant channel for the flow-induced vibration excitation in the core, it is important to carry out dynamic characterization of the coolant channel through vibration studies. Experimental and finite-element modal analyses have been carried out on a representative coolant channel, its 37 element fuel bundles and the fuel locators under simulated normal operating condition. This paper highlights the results and its potential use as diagnostic tool to monitor the health of coolant channel over its operating life in the core.

2. SCHEMATIC OF COOLANT CHANNEL AND THE INTERNALS

Figure 1 shows the schematic of the coolant channel and its internals. The end-to-end length of the channel is 11.625 m. The outer calandria tube and the internal pressure tube are both made of zircloy material. The end fittings are made of stainless steel. To keep the hot pressure tube and the warm calandria tube separated, there are four garter springs in the annular space. Important dimensions of the channel are as follows.

(i) Fuel bundle: 37 element, 496 mm long, weighing 26 kg/bundle, and 13 bundles/channel.
(ii) Pressure tube: 112 mm OD, 6.425 m long.
(iii) Calandria tube: 132 mm OD, 5.944 m long.
(iv) Fuel locator: 990 mm long and weight 42 Kg (two per channel).
(v) Shielding plug: 990 mm long and weight 56 Kg (two per channel).
(vi) Garter Springs: 4 tight fit on the pressure tube.

On a full-length high temperature and pressure test set up, vibration testing for modal analysis and vibration measurement was carried out with rated coolant flow conditions to assess the severity. For direct measurement on the pressure tube, circular holes were drilled on the calandria tube using trepanning tool at 6°clock positions. The positions of these holes were so chosen that they do not foul with the garter spring position in the annulus but are enough to pick up the response corresponding to higher modes of the pressure tube. Accelerometers were fixed on the pressure tube through the holes in the calandria tube and signals were acquired for online modal and vibration analysis.

3. MODAL ANALYSIS

The pressure tube, the calandria tube, and the end fittings were instrumented with accelerometers of sensitivity 100 mvolt/g and excited with portable reaction type electromagnet shaker. Sweep sine signal in the band of 5 to 100 Hz was given to the shaker mounted on one end fitting. Figure 2 shows a typical force input spectrum to the end fitting up to 50 Hz. The shape of the spectrum is typical to the end fitting dictated by its impedance offered to the shaker [1]. Figure 3 shows the frequency response function of the two ends fitting which is essentially an overhang beam. The first mode natural frequency of the two end fittings are 10.20 Hz and 15.25 Hz, respectively. Though the two end fittings are identical, the difference is basically because of the orientation of feeder pipes connected to two end fittings. One is horizontally connected and the other is vertically connected.

Figure 3 also shows frequency response function of the pressure tube vibration measured directly on the pressure tube. The first two modes are at 6.5 Hz and 16.70 Hz. The pressure tube modes are also seen in the frequency response function of the end fitting. That is to say that without direct access to pressure tubes in the reactor, it is still possible to monitor the dynamics of the pressure tube by monitoring vibration of the end fitting. Figure 4 shows the experimental mode shape of the pressure tube. The unsymmetrical shape is due to as-installed difference in the end condition on the two ends of the channel. Such unsymmetrical shape could be there in the actual reactor channel as well.

4. FINITE-ELEMENT MODEL OF COOLANT CHANNEL

A finite-element model of the coolant channel was developed on standard FE package by taking into account all the loading and boundary conditions. Figure 5 shows the FE Model. The pressure tube, calandria, and end fittings are discretized using 2-node axisymmetric-harmonic structural shell (shell 61) element. The individual mass of the fuel bundles and the water in the channel is uniformly distributed on the pressure tube [2]. The mass of fuel locator(s), shielding plug(s), and sealing plug(s) are lumped at the respective node locations of the end fitting. The grater springs between the pressure tube and calandria tube were modeled as rigid links. Modal analysis has been carried out for the design as well as for other boundary conditions of the channel as shown in Figures 6 and 7. These conditions are explained in Table 1. These conditions are selected on the basis of past experience and inservice inspection in some channels of different operating reactors. Some of these conditions are realizable in a coolant channel during its lifetime in the reactor. Others, like shifting of garter springs, missing of one or more garter springs, and bunching of garter springs, are considered only for academic exercise (cases 6, 9, and 10). These conditions are not feasible in the current generation PHWRs under normal circumstances. One more important condition likely in the channel is irradiation-induced creep. The effect of creep is to induce sag in the coolant channel. More on this is discussed in para 6.1. The first three natural frequencies for different conditions of Figures 6 and 7 are listed in Table 2.

4.1. *Channel dynamics in design condition*

The first two natural frequencies of the coolant channel model are 6.45 Hz and 17.62 Hz. These frequencies closely match with the experimental values shown in Figure 4 under simulated loading and boundary conditions. As the experimental channel is a full-scale setup, the close match of FE results with experimental results also ensures that the FE results are directly applicable to the reactor. Having tuned the FE model, it can be used for dynamic study under simulating loading condition such as fluid structure interaction, seismic analysis, shock response.

The important boundary conditions of direct relevance and that which can change the dynamics of the channel significantly are cases number 7 and 8, which pertain to effectiveness of bearings supports to the end fittings. It is quite likely that one or more bearing (out of four) may become partially ineffective during the lifetime of the channel or when the irradiation-induced sag in the channel is large. The loss of bearing support to the coolant channel reduces the channel frequencies significantly. Such a change is

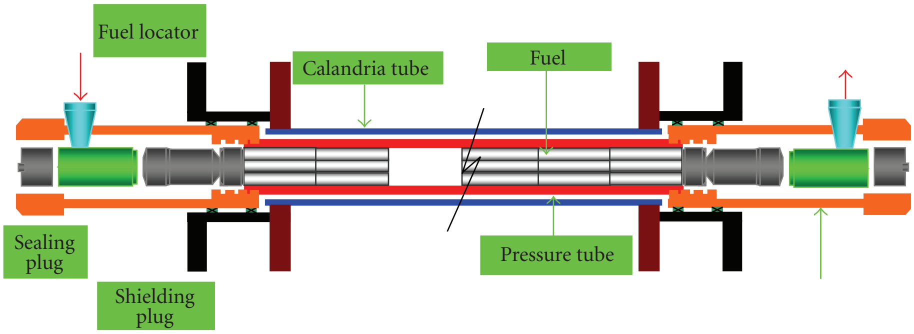

FIGURE 1: Coolant channel and its internals.

TABLE 1: Channel cases considered in the analysis. See Figures 6 and 7 for details.

Case 1	Channel in design condition and other conditions as per design
Case 2	Channel with 3 garter springs and other conditions as per design
Case 3	Channel with 2 central garter springs and other conditions as per design
Case 4	Channel with 2 outer garter springs and other conditions as per design
Case 5	Channel with 1 central garter spring and other conditions as per design
Case 6	Channel with NO central garter springs and other conditions as per design
Case 7	Channel with only one bearing support (outer) at the left end-fitting
Case 8	Channel with only one bearing support (inner) at the left end-fitting
Case 9	Channel with NO garter springs and one bearing support (outer) at the left
Case 10	Channel with NO garter springs and one bearing support (inner) at the left
Case 11	Channel with 4 garter springs displaced to center of the channel
Case 12	Channel with 2 pairs of garter springs displaced away from center

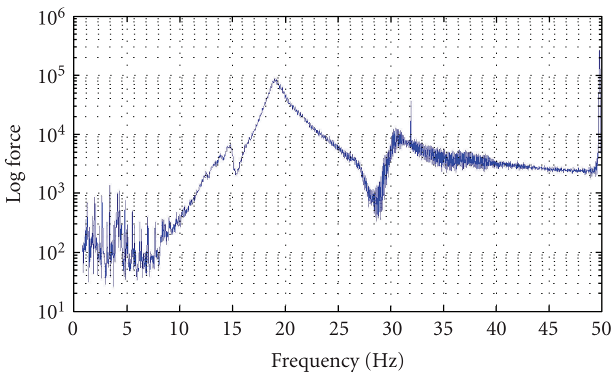

FIGURE 2: Shaker excitation to the coolant channel.

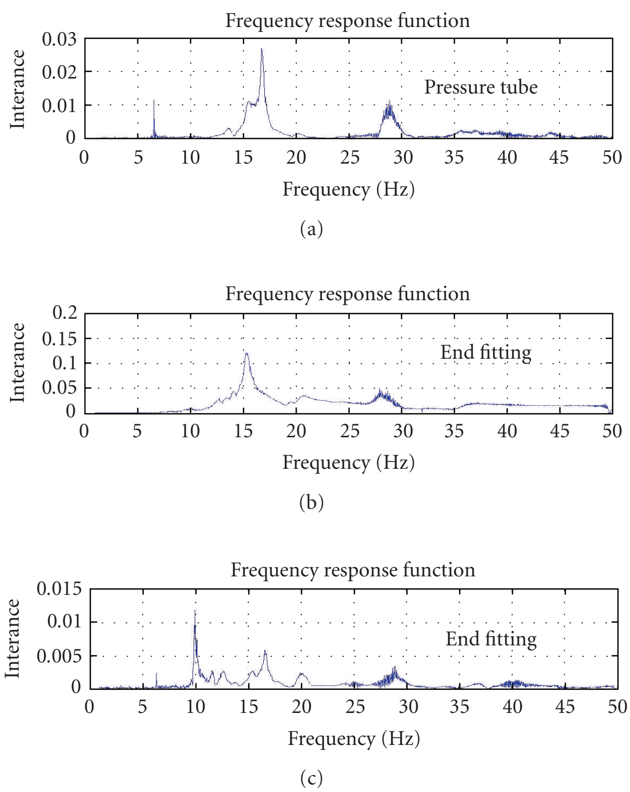

FIGURE 3: Frequency response function of pressure tube.

measurable and hence detectable for monitoring the condition of coolant channels.

5. RESPONSE OF THE CHANNEL DUE TO COOLANT FLOW

The channel response was measured during the rated coolant flow of about 30 Kg/sec at room temperature. Figure 8 shows the response of the pressure tube due to the flow excitation. The first two pressure tube modes at 6.25 Hz and 16.7 Hz, respectively, can be clearly seen. It has been seen that the

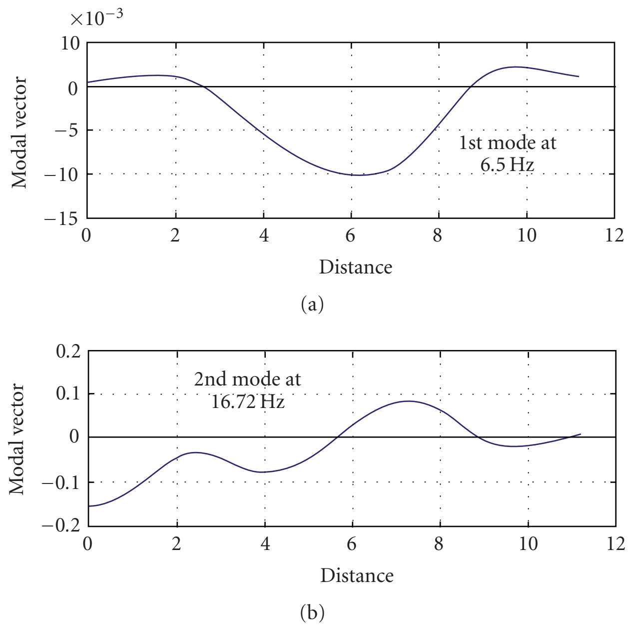

FIGURE 4: Experimental mode shapes of coolant channel.

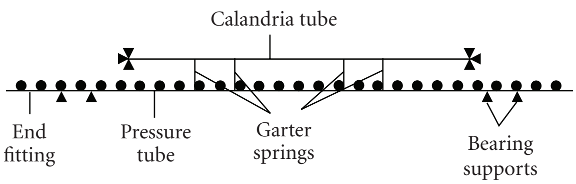

FIGURE 5: Finite element model of the coolant channel.

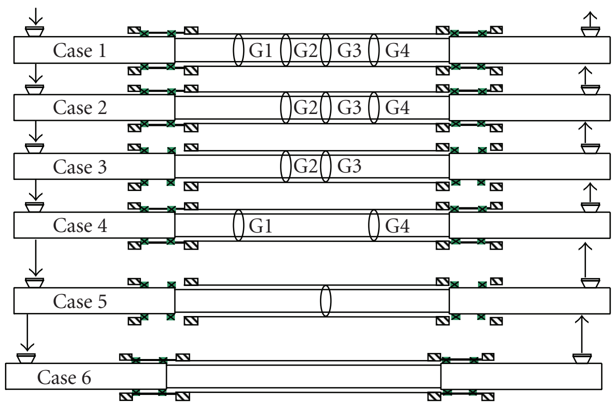

FIGURE 6: Coolant channel different garter spring fault scenario. G1 to G4 garter springs. Bearings shown in green.

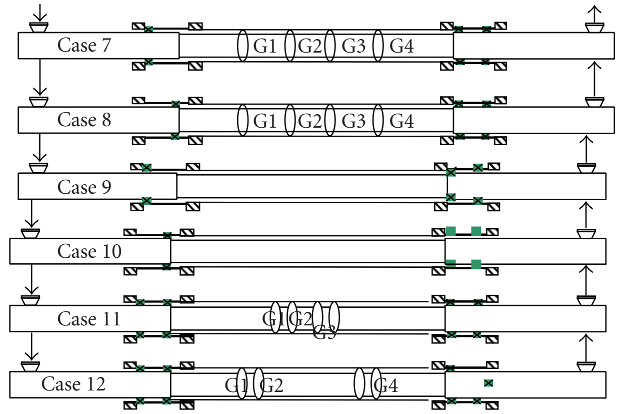

FIGURE 7: Coolant channel with different bearing faults and garter spring fault scenario.

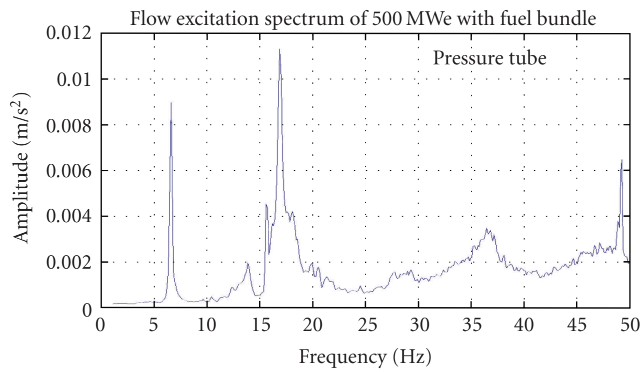

FIGURE 8: Flow excitation spectrum of pressure tube.

TABLE 2: Natural frequencies of coolant channel for fault scenarios.

Case	Frequency (Hz)		
	1st mode	2nd mode	3rd mode
Case 1 (design)	6.45	17.62	32.66
Case 2	6.42	17.05	30.05
Case 3	6.36	16.64	27.12
Case 4	6.41	17.59	25.65
Case 5	6.25	15.69	27.11
Case 6	4.99	13.55	27.30
Case 7	5.52	16.67	25.82
Case 8	4.02	17.53	31.92
Case 9	2.69	13.77	22.73
Case 10	2.66	13.55	26.43
Case 11	6.26	16.15	26.74
Case 12	6.41	17.59	29.71

amplitudes of the two modes decrease for lower than rated flow due to lower flow excitation [3]. The amplitude of pressure tube vibration during normal rate of coolant flow then was 6.3 microns. Figure 9 shows the response of the two end fittings. The dominant peaks in the two spectra correspond to the first mode natural frequencies of the two end fittings. These modes were identified as two end-fitting modes as explained in para 3.0 and shown in Figure 3. The first mode of the pressure tube can also be seen in the response spectrum of one of the end fitting at 6.25 Hz with small but distinct amplitude. The amplitude ratio of 6.25 Hz peak at center of the pressure and on the end fitting is 10 : 1 [4]. With modern sensors and signal analysis capabilities, it is possible to identify the first mode of the pressure tube on the end fitting.

Table 3

S. no.	Channel	Year of operation	Year of contact	1995	1996	1997	2000
1	L-14	1984	1996	—	8.125 Hz	—	—
2	M-07	1984	2000	—	8.030 Hz	8.030 Hz	8.156 Hz
3	O-02	1984	1997	—	8.060 Hz	8.125 Hz	—
4	P-13	1984	1996	—	8.156 Hz	8.156 Hz	—
5	D-15	1986	—	8.06 Hz	—	—	—
6	N-10	1986	—	8.03 Hz	—	—	—

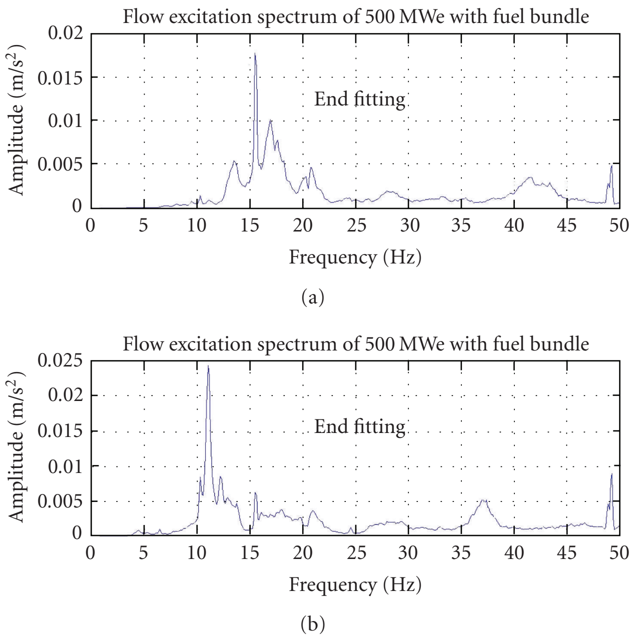

Figure 9: Flow excitation spectrum of end fittings.

6. CHANNEL RESPONSE CHARACTERISTICS AS A TOOL FOR DIAGNOSTICS

Having been able to measure the pressure tube vibration from the end fitting, this possibility opens the potential of diagnosing the health of the pressure tube during plant operation. In PHWR type of reactor, the fuel loading is an online process carried out by the special purpose machine, which latches onto the channel to replace the fuel bundle. The same machine can be made use of for measuring the end fitting response. If it is not found suitable, a separate campaign may be undertaken. The only requirement would be to operate primary coolant pumps. It has been observed that the shut down flow is not sufficient to excite the channel mode to the extent that the channel frequency can be detected on the end fittings.

As can be seen from the results of FE model of the coolant channel, any internal changes from as-installed/design condition of the channel results in change in its modal frequencies. The first mode is seen to be more sensitive to changes in the channel-bearing conditions and number of effective garter springs in the annulus. Diagnostics developed on the basis of channel vibration to detect changed garter spring position in earlier generation PHWR reactor is explained in next section.

6.1. *Nonintrusive diagnostic of coolant channels in earlier generation PHWR*

In the earlier generation Indian PHWRs, the concept coolant channels are similar to the new 540 MWe PHWR channels except that the sizes are different. Accordingly, the modal frequencies of the channel are different. There were two loose garter springs in the annulus of the coolant channel instead of four tight-fit type as in 540 MWe channel to keep the hot pressure tube and the cold calandria tube physically separated. The fuel used in these reactors was 19 element bundles weighing about 16 Kg, which are similar to CANDU's 19 element fuel bundles.

During the commissioning activity, when the channels are subject to be hot conditioning, there is no fuel in the channel. In such a condition, the loose garter springs are free to slide on the pressure tube. For hot conditioning, hot fluid flows in the pressure tubes and hence induces vibration in the tube. Due to flow-induced vibrations in the tube, the garter springs got shifted in number of channels. This displacement resulted in lowering the design gap of 8.0 mm between the two tubes when the fuel is loaded. This and irradiation-induced creep in the tube led to premature contact between the tubes in loaded condition. Such a contact is considered to be hazardous for the safety of the reactor.

To identify the contacting channels in the core, a nonintrusive vibration technique was developed based on the change in natural frequency of the channel. In this technique, one end of the channel (end-fitting) is excited by a portable shaker and response is measured from the other end of the channel. The excitation was tuned to excite only the first mode of the channel. With this technique, the entire core was screened to detect change in the first natural frequency. As low-level excitation is given to the channel, the neighboring channel does not get affected nor do they influence the channel under excitation. Such screening campaign was carried out on more than 2000 channels, repeating two to three times on the same channel over the period of several full power years. It was found that in the channels with high creep, the first natural frequency of the channel increased to a higher value. The table below shows the trend of the natural frequencies with high and low creep channels.

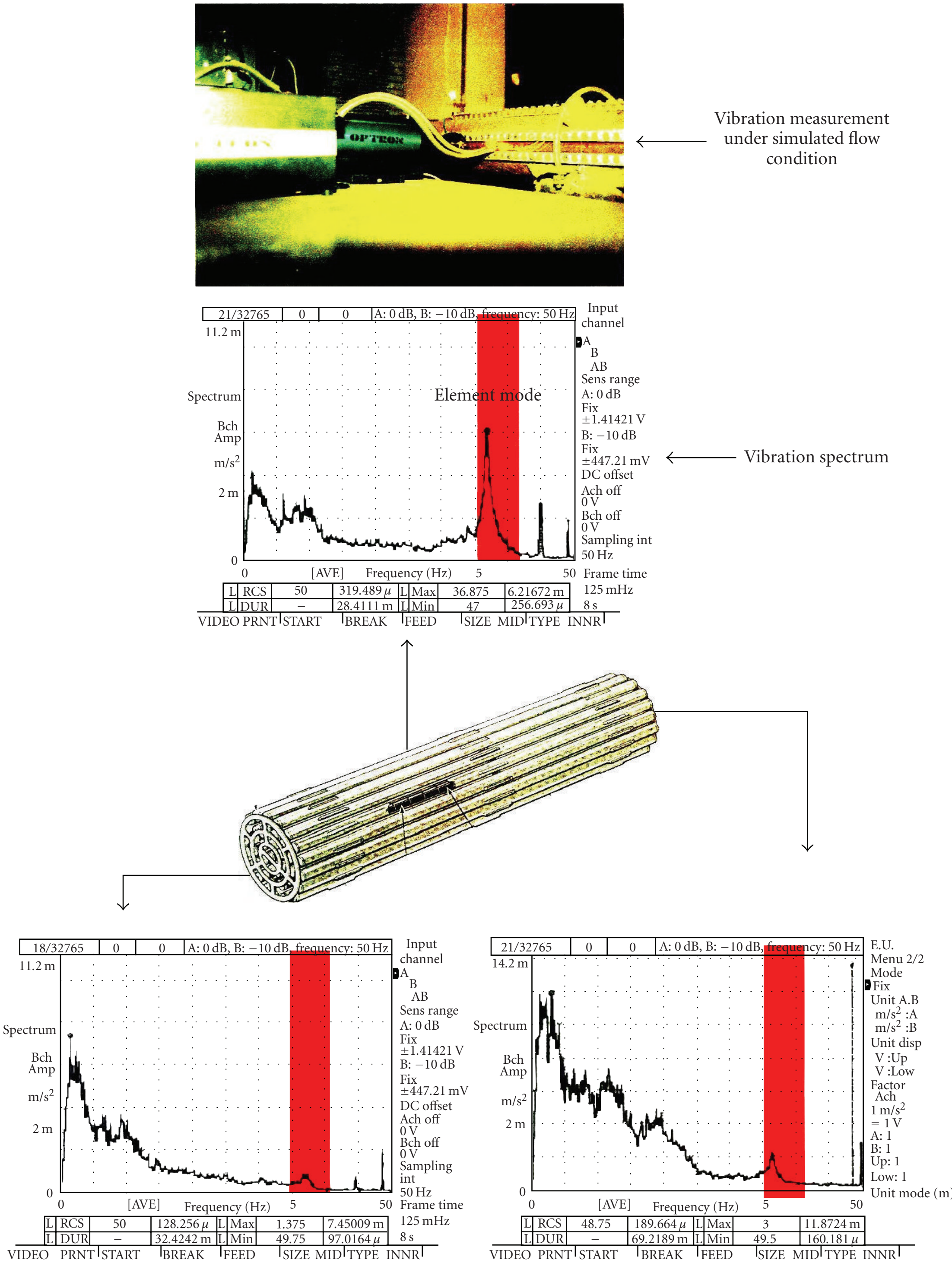

FIGURE 10: Experimental results of 37 element bundle vibration under flow excitation.

The first mode natural frequency of the coolant channel of 235 MWe PHWR is 7.95 Hz as against 6.5 Hz for the 540 MWe channels. Due to irradiation-enhanced creep and due to displaced garter springs, some of the channels had sagged (elastic and plastic) by more than 14 mm in the center. The deformation due to creep had set the channels into a permanently sagged condition. Such channels showed an increase in the natural frequency. The pace of increase was found to be very slow in a healthy channel whereas in a highly sagged channels, the increase was found to be relatively fast.

Some of the typical channel frequencies and its changes over the period of time are shown in the table below. All the channels shown in the table below were removed from the core in the respective years for postirradiation inspection of suspected contact based on analytical estimation of time of contact. In these, some are high flux and some are low flux channels. Except for channel D15 and N10 other four channels were found contacting. It may be seen from the table that all the four contacting channels had first-mode frequency which was equal to or more than 8.125 Hz, which was an increase of 0.175 Hz from normal. Since the smallest measurable frequency by the analysis system was 0.03 Hz, it was possible to trend the change in the frequency accurately. Hence, the data bank of the channel natural frequency was reliably used as a diagnostic tool to identify healthiness of a channel.

7. FUEL BUNDLE VIBRATION

The fuel bundle in the 540 MWe reactors is made of 37 elements, which is similar in construction to standard CANDU fuel. In Indian PHWR channels, there are some changes with respect to larger CANDU reactor wherein there are 13 fuel bundles per channel instead of 12 and there is fuel locator on the upstream and downstream of the 13 bundles, which is free in the channel and so is in contact with the first and the last fuel bundle. The need for a fuel locator has come as a requirement for the fueling machine design.

In view of the new in-core components in the channel, a study was carried out to investigate its effect on fuel vibration performance. Such a study was carried out in a specially erected low-temperature setup to measure fuel and fuel locator vibration by optical vibration transducer through a Perspex window cut in the setup. All the fuel boundary conditions were simulated and the dynamic head of the coolant flow was maintained in the setup. Flow turbulence being the main source of excitation to the in-core components, the fuel and fuel locator vibrations were measured at different flow rate through the channel.

Figure 10 shows the picture of optical probe measuring the fuel vibration. The figure also shows the three-vibration spectrum of the first bundle measured at the front, middle, and at the rear of the bundle. The dominant (marked) peak in the spectrum corresponds to the first bending mode of the fuel element, which is at 36 Hz. The bending mode of the element is excited at about 70% of the rated flow. It was observed that the frequency band of flow excitation reduces with increase in flow rate [5]. At 100% flow, the excitation remains confined up to 30 Hz. The rocking mode [5] of the bundle at 2.62 Hz can be seen in the three spectra shown in Figure 10. The amplitude of vibration of the element at 36 Hz was about 10 micron.

8. CONCLUSIONS

The coolant channel is the heart of PHWR type of reactors. In PHWR, normal operating life of a channel is 20–25 years. Besides the wear and tear in the channel due to continuous operation, they are also subjected to irradiation-induced damages to the material of the channel and associated substructures. It is hence desirable to monitor the changes happening in the channel from the reactor safety point of view. The easiest method is to check changes in the dynamics of the channel. The experimental and modeling study on the coolant channel has been carried with an aim to understand the dynamics of the channel. The measured natural frequencies identified in the modal analysis and from the response analysis of the channel during flow excitation can be used for monitoring the health of the channel.

Changes in the support conditions (garter springs), large sagging deformation, premature contact, and other mechanistic changes also influence the dynamics of the channel. A number of such changes/deviations have been observed in Indian PHWR channel over its operating life. These changes limit the safe operating life of the channel to less than 15 years. The study carried out in this paper aims to demonstrate the possibility of detecting the changes that happen in the channel. As an example, detecting contact between hot pressure tube and cold calandria has been illustrated based on actual measurement and inspection.

The fuel bundles in the channel are also subjected to flow-induced vibration. It has been demonstrated in the paper that under simulated test conditions, it is possible to detect fuel vibration. Such an investigation is especially useful during the design phase of the fuel. There are number of reported fuel failures in operating nuclear reactors due to flow-induced vibration. Detection of the bending mode of the fuel element is perhaps reported for the first time through this paper. Such fuel vibration overextended period of time may result in fret-related damages in the fuel and in the channel that support the fuel.

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