Vibration Analysis of Hydro Mechanical Structure Upper Kotmale Hydropower Plant

T. Namba

Abstract: During the commissioning test of the units in Upper Kotmale hydropower station, high vibration response level was observed at some part of the equipment and the civil structure. Several investigations and measurements have been done to grasp the actual situation and vibration level of each component. Based on the measurement result, countermeasures to mitigate the vibration level was studied by using FEM. Based on the analysis result, actual countermeasure was taken up during the outage period in March 2013 by providing a stiffener around the penstock. In this document, vibration measurement result, FEM analysis for establishing the countermeasure, and the evaluation on the effectiveness of the countermeasure are summarized.

Keywords: Hydroelectric, Penstock, Vibration, Resonance, FEM

1. Introduction

During the commissioning test, high vibration level was observed at some part of the power station. To reduce the vibration level, several field investigations and measurements have been done. Based on the field measurement, countermeasure was studied and established by analytical approach. In this paper, summary of the field measurement result, analysis result, and the countermeasure taken up are described.

2. Vibration Measurement during the Commissioning Test

In the preliminary vibration measurement by using the handy vibration meter during the unit operation, high level vibration was measured at the penstock sections. Measurement positions are as shown in Fig.1. The measurement result is tabulated in Table-1.

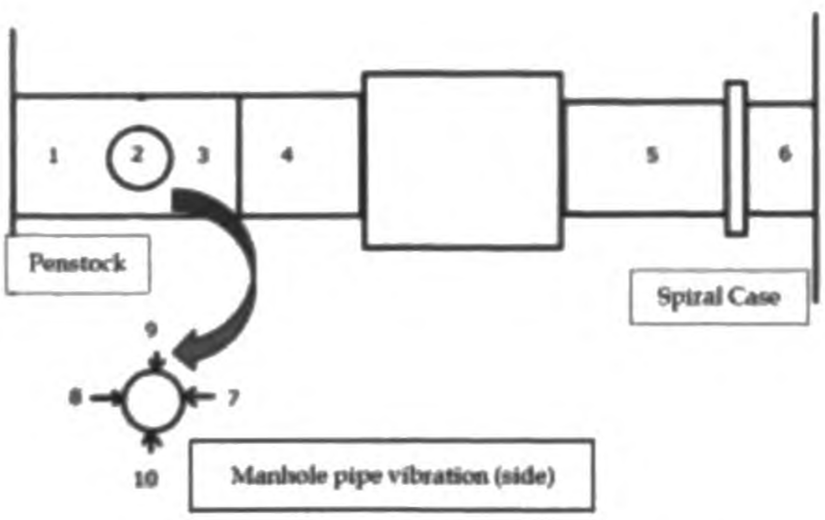


Figure 1 - Vibration measurement position by using handy vibration meter

Table1 - Vibration measurement result (acceleration measurement) (m/s^2)

Position	1	2	3	4	5	6	7	8
Apr.15 2012 (Before countermeasure)	48.7	22.0	32.0	16.4	7.4	5.6	32.2	31.2

By using the measurement result of position 1 to 6 shown in Table 1, flow directional vibration variation is drawn as Fig.2.

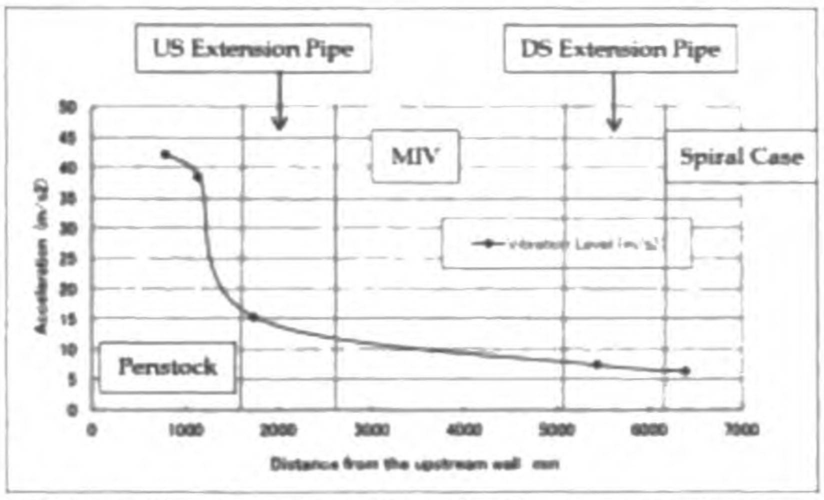


Figure 2 - flow directional vibration variation

Considering the high vibration level in the penstock area, resonance of the penstock structure with the excitation frequency generated by the turbine operation could be a cause of the vibration. The excitation frequency generated by turbine operation is as follows.

Excitation frequency=nZr=600*18/60=180Hz

Where
N : rotational speed (r/sec)=600/60

Teruaki Namba., M. Eng. (Mechanical)
Manager of Water Turbine Design Section III
Hitachi Mitsubishi Hydro Corporation.

Zr: number of runner blades = 18

To grasp the vibration level on the structural components and the power house, following measurement was taken up in May 2012.

- Tapping test of the structural components including penstock and turbine.
- Vibration measurement of the floor and the structural components.

2.1 Tapping Test

Natural frequency measurement was done by hammering the 4 sections (Section A, B, C, and K). To investigate the longitudinal response variation, measurementwas also done at 16 positions along the water flow direction from penstock to spiral case. To measure the phase angle at each section measurement was done at 16 positions circumferentially in the way that sensor1 was fixed in the position while changing the position of sensor 2.

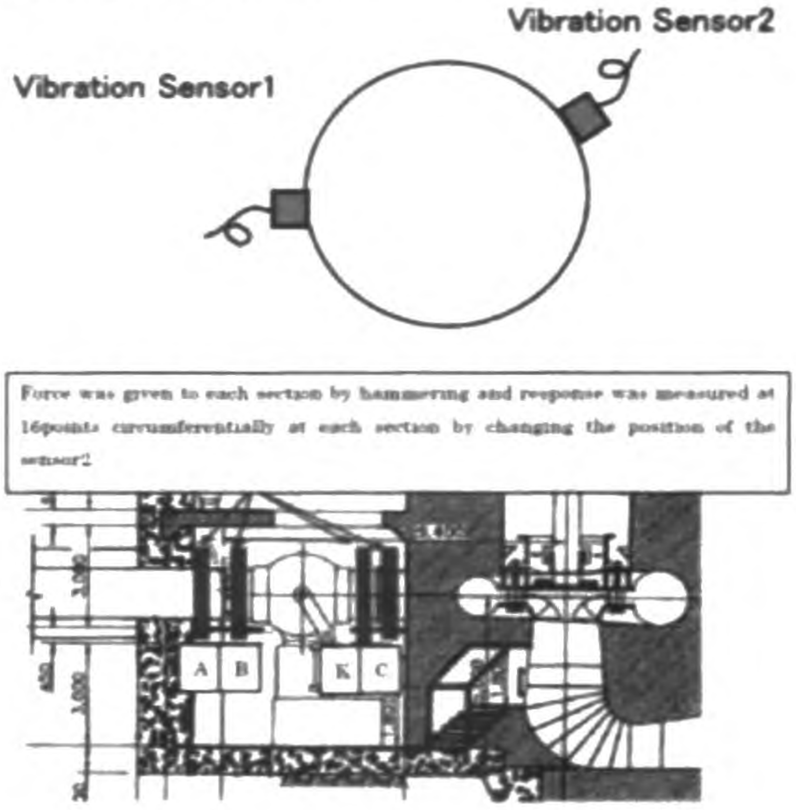


Figure 3 - Position Measured in the Tapping Test

Response spectrums and vibration mode shape obtained as a result of tapping test are attached in Fig.4. As a result of the tapping test, the following consequences are figured out.

- Penstock section has a natural frequency of 181.5Hz. That is close to the excitation frequency of 180Hz.
- Vibration mode of the penstock section at the frequency of 181.25Hz is 4ND shape.
- Vibration response level of penstock section is significantly higher compared to extension piece sections and spiral case sections.

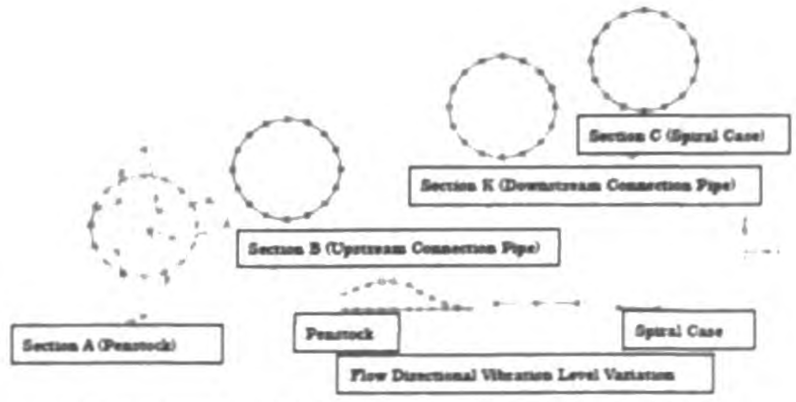


Figure 4 - Vibration mode at 181.5Hz

2.2 Vibration Measurement in Unit Operation

After the tapping test, vibration level during unit operation was measured. The measurement was done at the same sections and position as the tapping test. The following becomes clear as a result of the measurement.

- Penstock vibration level measured at the highest position is about±35µm in vibration displacement.
- Penstock is vibrating in its natural frequency in the 4ND vibration mode as measured during the taping test.
- Vibration response level in the penstock section is significantly higher than that of extension piece and spiral case.
- Vibration level is governed by nZr Component and the vibration response level against nZr excitation force governs the vibration level as shown in Fig.6..

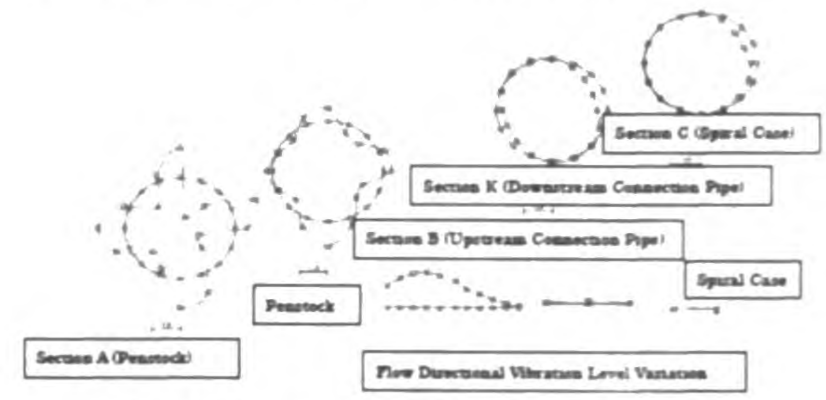


Figure 5 - Vibration mode shape during unit operation (nZr=180Hz component)

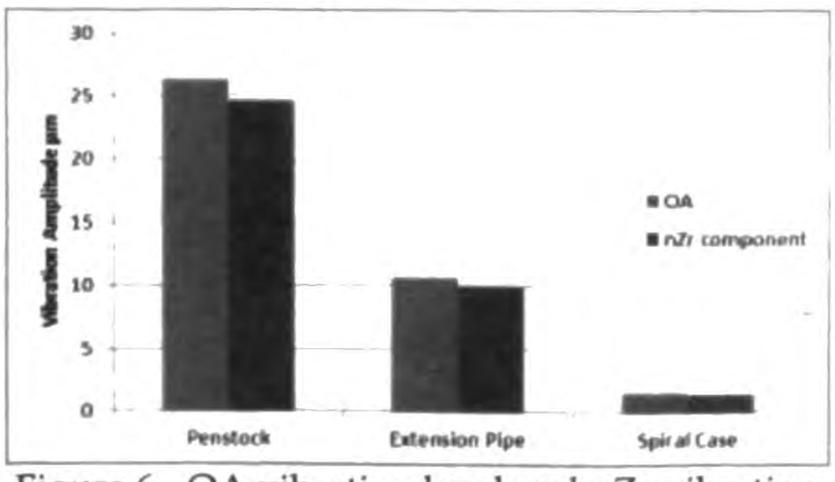


Figure 6 - OA vibration level and nZr vibration component

3. Countermeasure to Reduce the Vibration Level

3.1 Numerical Analysis Model

To reduce the vibration level, investigation was made to establish a countermeasure by using FEM. The investigation was aimed at establishing a countermeasure plan by providing a reinforcement around the penstock and avoiding the resonance against the excitation force of 180Hz. The calculation was made by modelling the penstock and upstream connection pipe. Calculation model is as shown in Fig.7. At the inlet valve side, fixed support was given as the boundary condition since the vibration in the inlet valve side is negligible according to the field measurement result, and the mass of the inlet valve is large. At the penstock side, stiffness was given at the concrete support position and the stiffness was adjusted by comparing with the field measurement result so that the most appropriate calculation result can be obtained. Fig.8 shows the comparison of the vibration mode shape between the field measurement and the calculation.

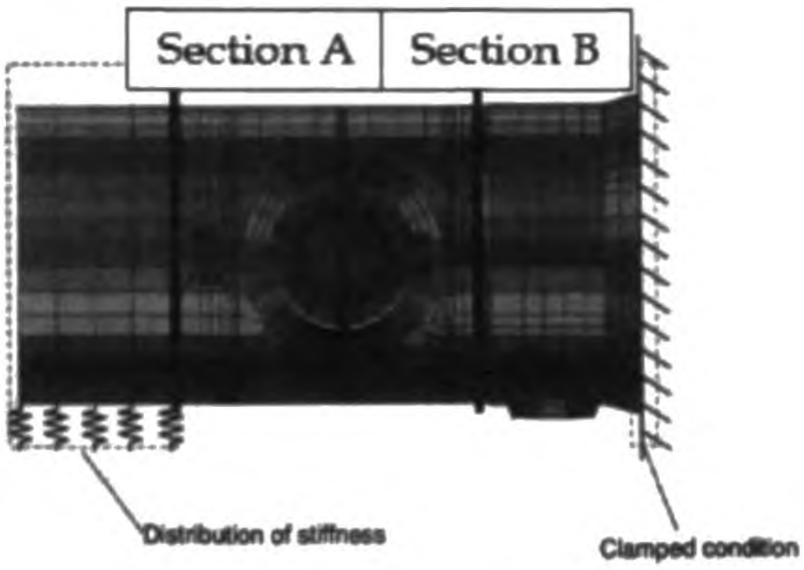


Figure 7 - Analysis Model

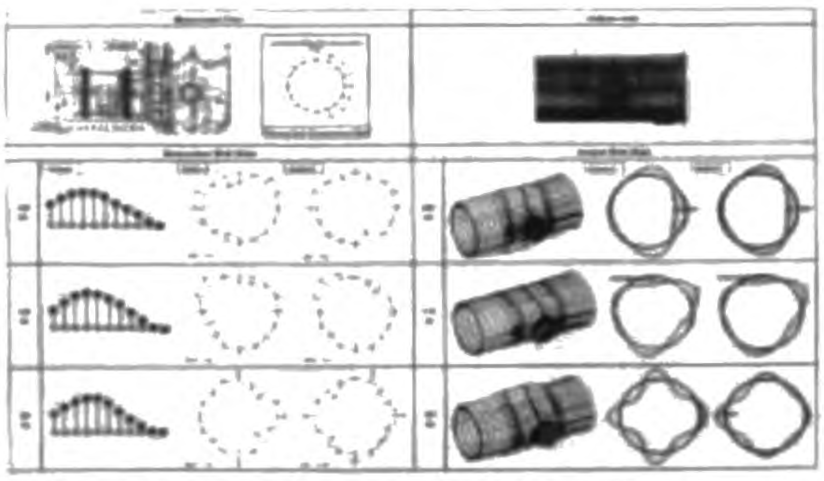


Figure 8 - Comparison between the natural frequency between the measured and calculated value

By using the adjusted concrete support stiffness, natural frequency calculation was done for the 3 models shown in Fig.9.

	Detail of reinforcement	Analysis model
A	Circumferential rib (t=25mm, h=200mm), at the section of maintenance hatch.	
B	Circumferential rib (t=50mm, h=200mm), at the section of maintenance hatch. The edges of the rib are welded to the surface of maintenance hatch.	
C	Three ribs (t=25mm, h=200mm)	

Figure 9 - Calculation model used for the evaluation

3.2 Natural Frequency Calculation

Mechanical structures have various natural frequencies. Fig.10 shows the natural frequency calculation result. 4ND natural frequency vibration mode, which is close to the excitation frequency and considered to be in resonance, can be increased by providing ribs, but 3ND vibration mode, which resides below the excitation force frequency, also increases and comes up to around excitation force frequency of 180Hz. To mitigate the vibration level, stiffener shall bedesigned so that the natural frequency of the structure that has high response level and may result in resonance can secure enough avoidance ratios against the excitation force frequency.

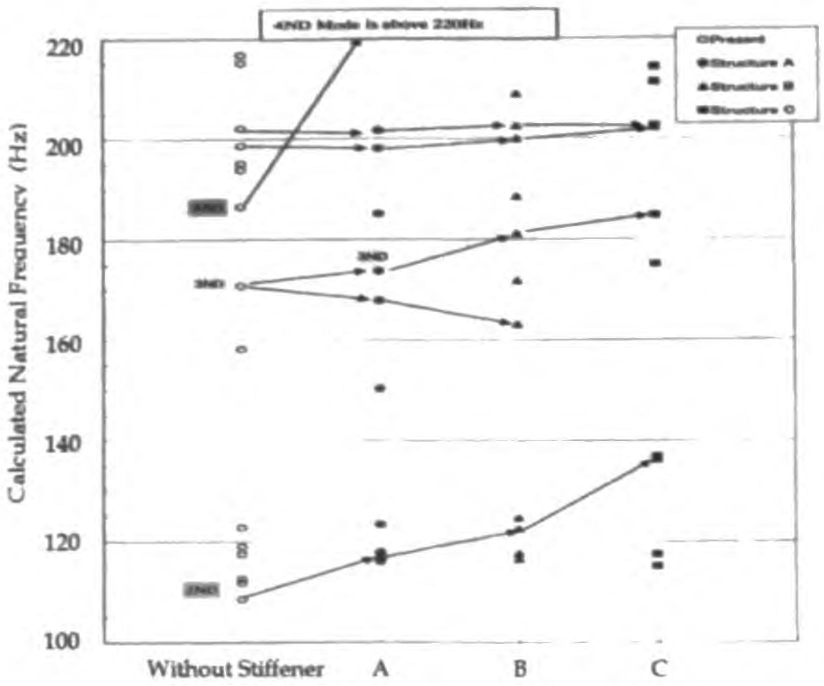


Figure 10 - Calculation Result of Natural Frequency

To grasp the response level of the vibration modes, excitation force was given at 3 different positions, and response analysis was done for each case as described in Fig.11. The calculation results are summarized in Fig.12.

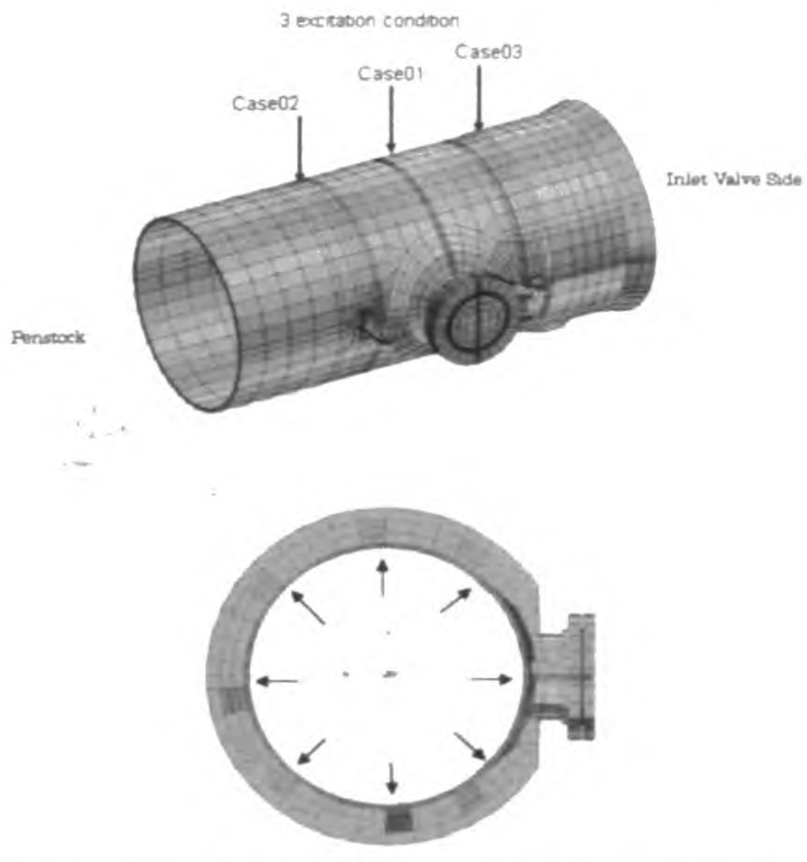
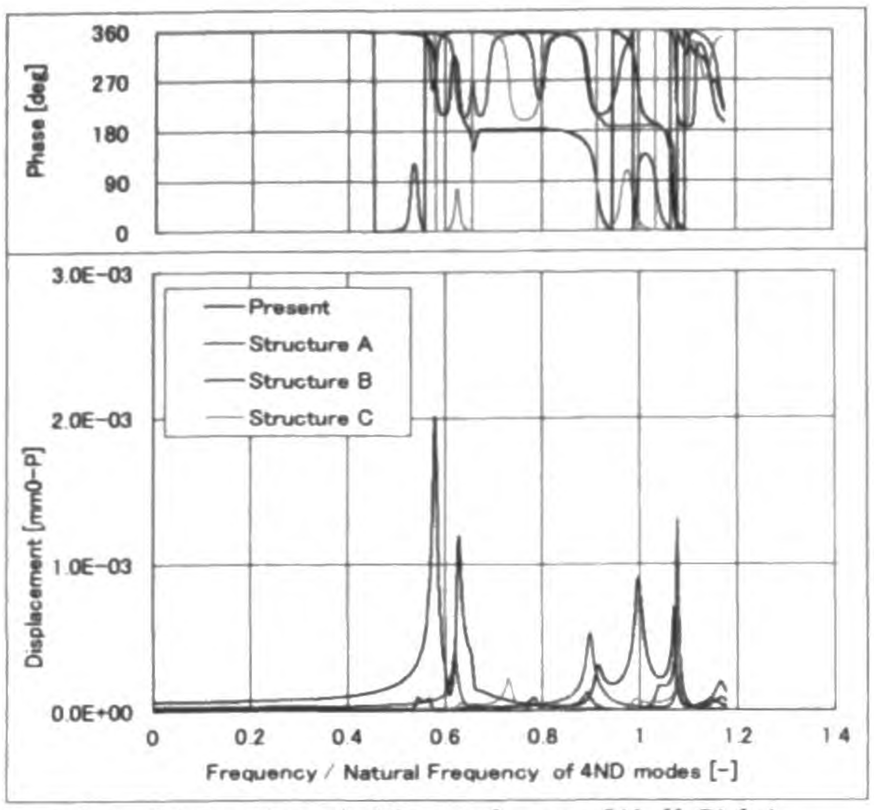
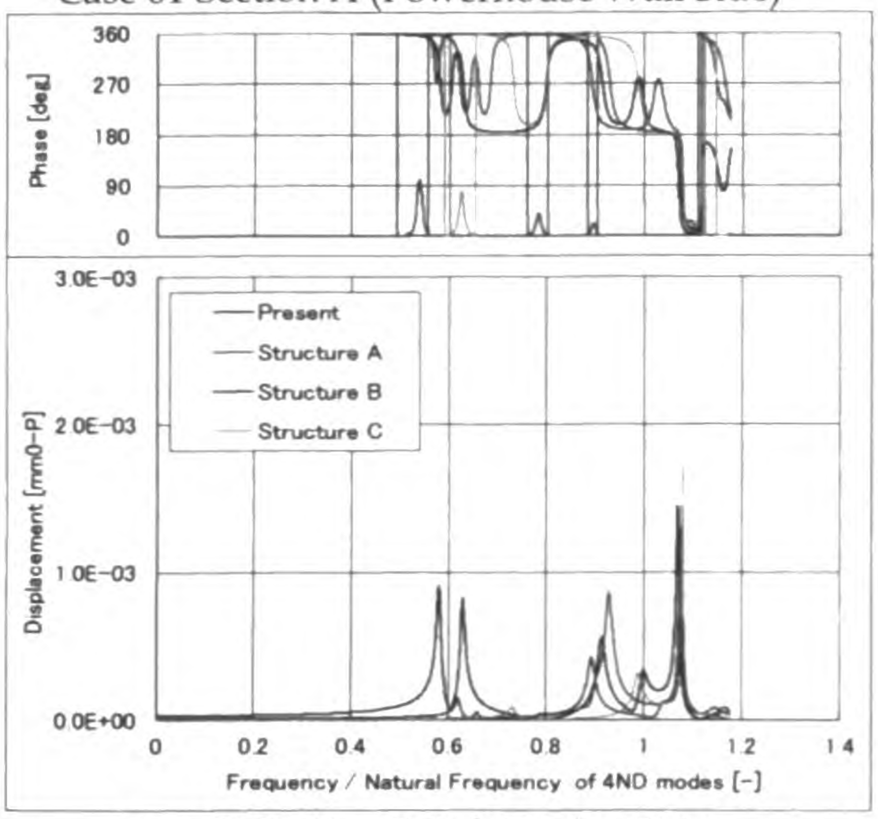


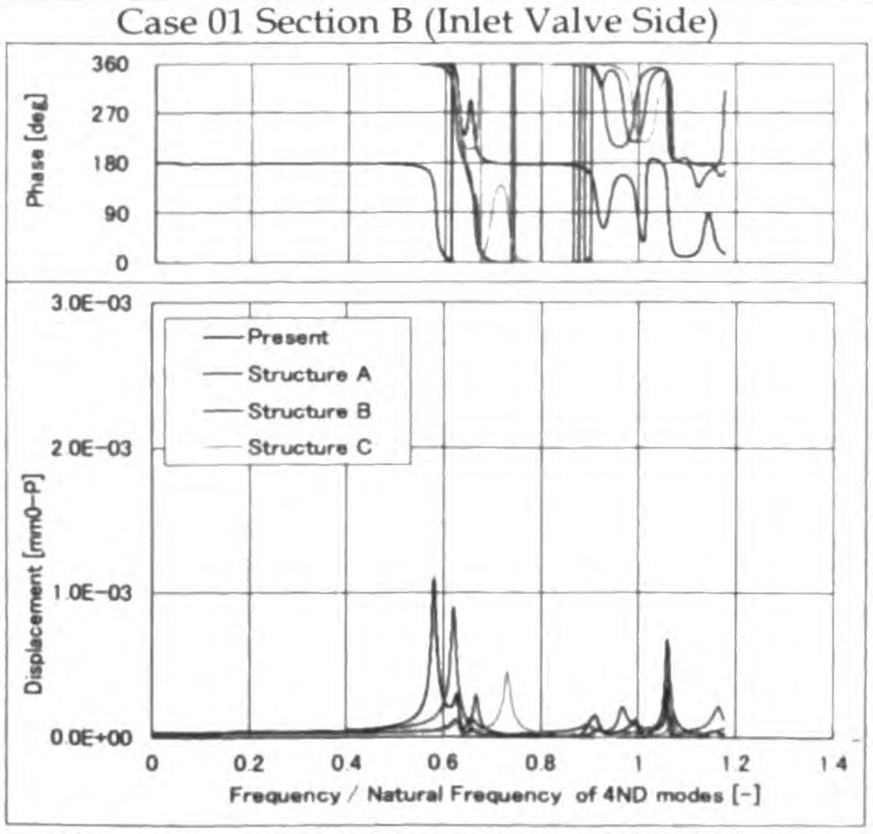
Figure 11 - Excitation condition used for the calculation



Case 01 Section A (Powerhouse Wall Side)

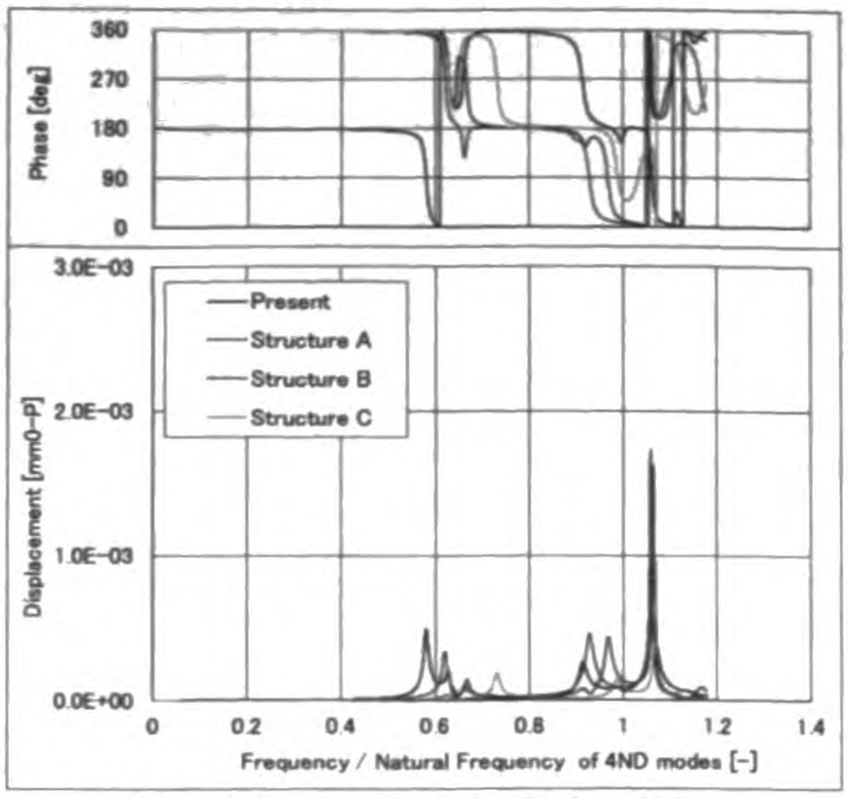


Case 01 Section B (Inlet Valve Side)

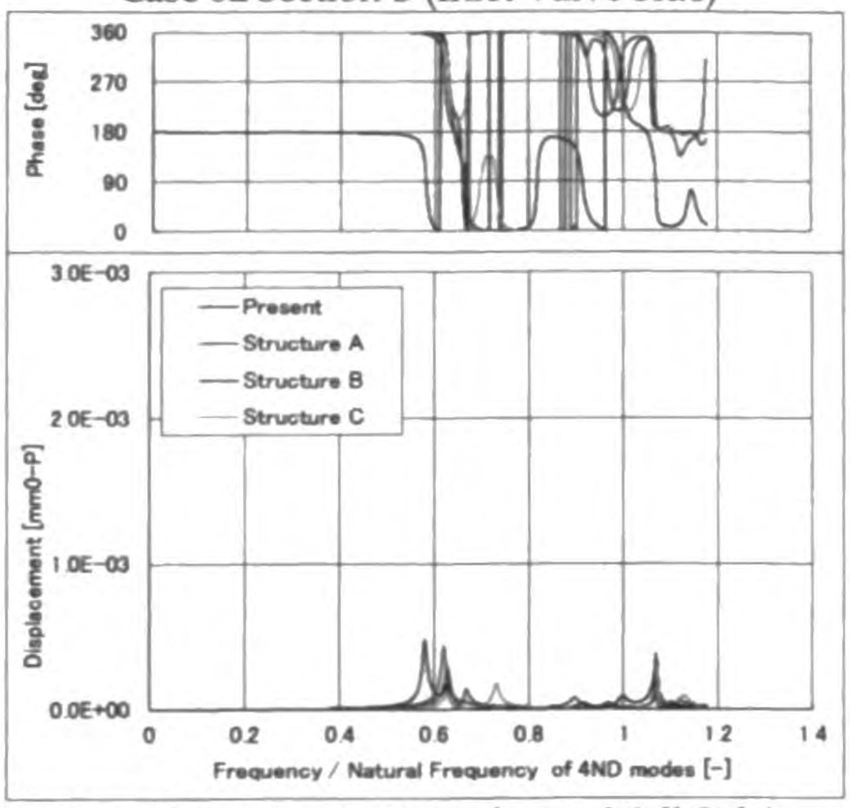


Case 02 Section A (Powerhouse Wall Side)

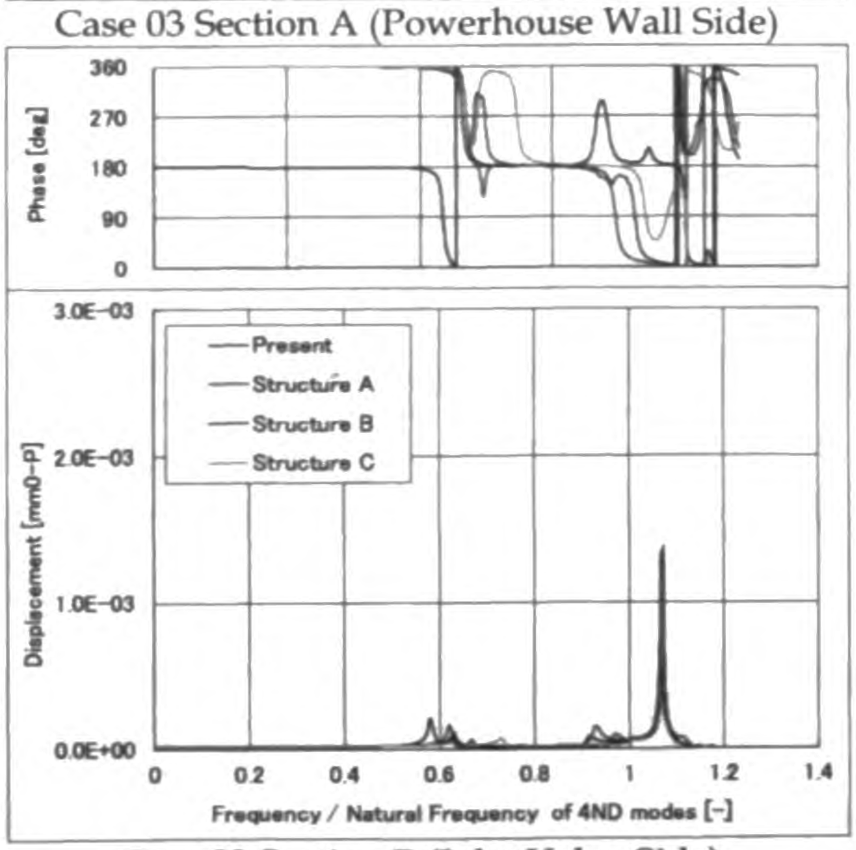
Figure 12 -Vibration Response Analysis Result–cont'-



Case 02 Section B (Inlet Valve Side)



Case 03 Section A (Powerhouse Wall Side)



Case 03 Section B (Inlet Valve Side)

Figure 12 -Vibration Response Analysis Result

To reduce the vibration level in unit operation, natural frequency which has high response level shall not reside close to the excitation frequency. In Fig.12, abscissa axis is normalized by using the natural frequency of 4ND mode which is just on the excitation frequency of 180Hz. By providing stiffener, this 4ND mode can be increased to certain level and the resonance of this vibration mode can be avoided. But at the same time, other natural frequency that resides below 180Hz increases as the stiffness of the structure increases, and comes closer to 180Hz. In case 01 and 02 Section 2, the calculation result indicates the possibility that another natural frequency comes up closer to 180Hz and may result in resonance at 180Hz. Therefore we concluded that making the stiffness of the structure in excess is not favourable to give enough resonance avoidance ratios for all the natural frequencies against the excitation force frequency, and "Structure A" is the most appropriate way to reduce the vibration level as it does not have high response level natural frequency around 180Hz according to the calculation result. Countermeasure for vibration was taken up in March 2013 during the outage period based on "Structure A" of this calculation.

Figure 13 - Installation of stiffener

4. Vibration Measurement after Countermeasure

After the implementation of the countermeasure, vibration measurement was done to see the effectiveness and the measurement result was compared with the previous values measured before the countermeasure. Measurement of the vibration on penstock and spiral case was done at the same position as described in Fig.1. The measurement results are tabulated in Table-2 in comparing the result before and after providing the stiffener.

Table-2 Vibration measurement result (acceleration measurement) (m/s^2)

Position	1	2	3	4	5	6	7	8	9	10
Apr.15 2012 (Before countermeasure)	48.7	22.0	32.0	16.4	7.4	5.6	32.2	31.2	-	-
April 4 2013 (After countermeasure)	20.5	11.8	18.7	13.8	11.4	5.8	46.0	28	13	12.4

Floor vibration was measured at the position described in Fig.14 on B2 floor. The measurement results are tabulated in Table 3.

Table-3 Vibration measurement result on B2 floor (Acceleration measurement m/s^2)

	B2-01	B2-02	B2-03	B2-04	B2-05	B2-06
Apr.17 2012 (Before countermeasure)	7.4	7.2	3.9	3.3	1.0	3.1
Apr.6 2013 (After countermeasure)	3.3	4.3	2.2	1.7	2.6	1.1

	B2-07	B2-08	B2-09	B2-10
Apr.17 2012 (Before countermeasure)	-	2.7	-	4.1
Apr.6 2013 (After countermeasure)	1.1	0.7	2.4	0.7

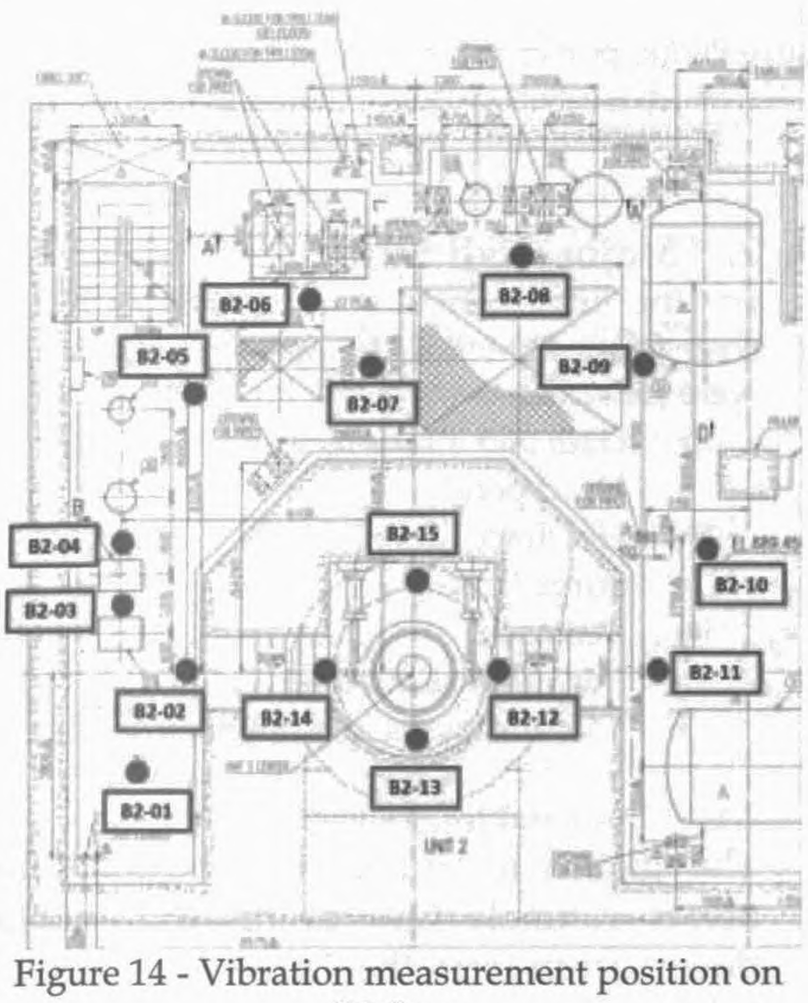


Figure 14 - Vibration measurement position on B2 floor

Based on the measurement result, vibration level on equipment havesignificantly reduced after the countermeasure where the vibration level had been originally high. Manhole side vibration remains high even after the countermeasure. This is considered to be affected by the vibration mode of the structure that resides around 180Hz for which enough resonance avoidance could not be given by providing the stiffener.
As the vibration on the penstock reduced, vibration level on the floor also reduced accordingly.

5. Conclusions

Vibration and noise measurements were made before and after the implementation of the anti-vibration countermeasure. By comparing the measurement results, following is the conclusions we obtained.

- Vibration level of the penstock have reduced to the amount of approx. 50% after the implementation of the countermeasure except for the vibration level at the side of the penstock manhole pipe.
- Penstock manhole pipe vibration level remains unchanged. This is thought to be due to the vibration mode that resides around 180Hz in which vibration level around the penstock manhole is large.

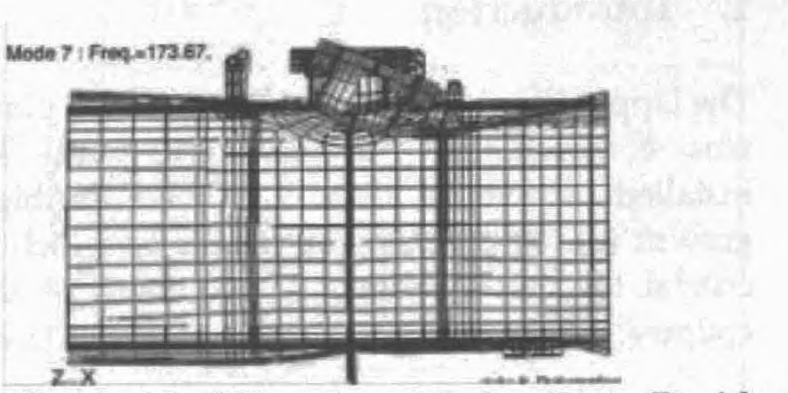


Figure-15 Vibration Mode that Resides around 180Hz after providing stiffener. (FEM result)

- Vibration level of the spiral case and the extension piece to spiral case, where the vibration level was not high originally, remain in the same level after the countermeasure.
- Vibration level on B2 floor, where the vibration level was significantly higher than the other floors before the implementation of the countermeasure, have significantly reduced. Reduction amount of vibration level is roughly about 50% to 70%.