DYNAMIC PROPERTIES OF A LARGE ARCH DAM AFTER FORTY-FOUR YEARS OF COMPLETION

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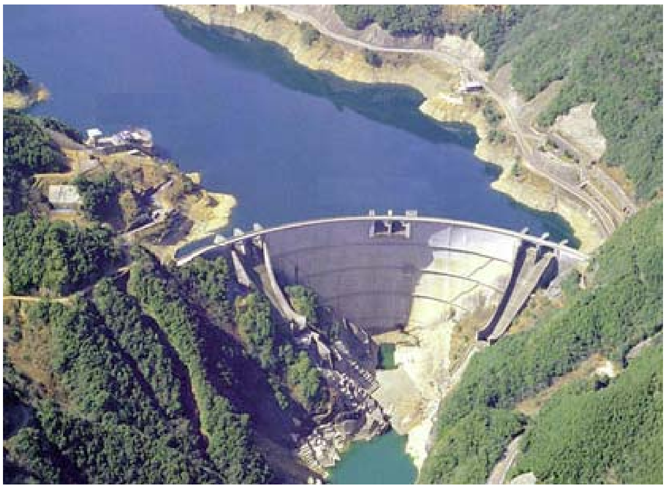
ABSTRACT :

To evaluate seismic safety of an aged concrete arch dam, present dynamic properties have been continuously measured by ambient vibration test for more than one year, which are employed for calibrating a finite element model of the dam-foundation rock-reservoir water interaction system, as well as for collecting the fundamental data about vibration test based structural health monitoring. Hitotsuse arch dam, treated in this paper, was completed in 1963 (aged 44 years), and its height is 130m. To obtain the present dynamic properties, two kinds of ambient vibration test are conducted: one is the high-density vibration array test to obtain mode shapes of the dam. The other is the long-term continuous vibration-measuring test to evaluate the seasonal changes of the natural frequencies. In this paper, we mainly show test results on identification of the lowest three mode shapes, and seasonal changes of the natural frequencies, and discuss on the seasonal changes of the natural frequencies mainly ruled by the reservoir water level, and the comparison between the results from the present ambient vibration test and past forced vibration test and earthquake records.

KEYWORDS: arch dam, dynamic property, ambient vibration, power spectrum, mode shape

1. INTRODUCTION

Kyushu Electric Power Company (KEPCO) has two large arch dams to generate electricity, which were built for 40 years or more. In the last four decades, the prediction technique of both input earthquake excitation and earthquake responses have been significantly well-developed for arch dams. Moreover, it is pointed out that the probability of occurrence of the earthquakes might be high around the dams. To operate the dams continuously over the long period in the future, it is important to ensure the safety against large earthquakes by using the latest prediction schemes, and also to develop structural diagnosis technique for properly detecting structural damage due to the aging and earthquake attacks.



Picture1 Hitotsuse arch dam

At present, for safety inspection of the dams, the water leakage and the deformation on the whole of the dams are usually monitored, however, the most reliable inspection is the visual inspection where the engineer observes the surface of the dam regularly. But it might be difficult to find the damage in large or complex structures; e.g., the damages might not be visible, such as those on the upstream side under water level, on the contact surface of the concrete blocks, or on the contact part between the dam and base rock. To solve the difficulty, it is desirable to develop damage detection technique on the entire structure by a simple measurement. The structural health monitoring based on the ambient vibration test is one of the effective solutions, where damage can be detected from the change of natural frequencies and modal participation factors of the dams.

On the background above, we have conducted two kinds of ambient vibration test to evaluate seismic safety of the concrete arch dams, as well as to collect the fundamental data for developing structural damage detection based on ambient vibration test. This paper treats one of the two large arch dams called Hitotsuse arch dam shown in Picture 1, and these present modal identification results are compared with the results of the forced vibration test conducted 42 years ago after two years of completion [8]. We also analyze the fluctuation of natural frequencies due to the reservoir water level varying or temperature change. For all modal identifications, a cross spectrum based modal identification schemes are employed, which are proposed by one of the authors [1][5][6]. These present dynamic properties obtained here will be employed for calibrating a finite element model of the dam-foundation rock-reservoir water interaction system for earthquake response analysis.

2. OUTLINES OF THE DAM

Hitotsuse dam was constructed for hydroelectric generation in Kyushu region, south part of Japan by KEPCO, which was completed in 1963. The power plant generates 180MW and the capacity (of total storing water of the reservoir) is $261{,}315 \times 10^3 m^3$. As shown in Figure 1, the height and the crest length of the dam are approximately 130m (the crest elevation is 203.00m above the sea level) and 418m, and the dam consists of 5 by 27 blocks with four inspection catwalks (these elevations are 174.00m, 146.00m, 118.00m, 90.00m above the sea level, respectively) and an inspection gallery (its elevation is 73.00m above the sea level). As shown in the section of Figure 1, the water level varies from 170.00m to 200.00m above the sea level.

3. MEASUREMENT POINT AND PROCEDURE

3.1. High-density vibration array test (HDV test)

The HDV test was carried out on 21-22 February 2007 to identify mode shapes on whole of the dam. Figure 1 also shows a downstream view of the dam with these vibration measuring points. In the HDV test, 97 array points are set on the downstream surface of the dam, and ambient vibration was sequentially measured 20 times with replacing eight portable accelerometers. The measuring time at each point is fixed to 10 minutes. The 20 modal identification results are synthesized to obtain mode shapes on whole of the dam by using the data at two fixed points which are obtained in the long-term vibration-measuring test (the LTV test) as described in the next subsection.

3.2. Long-term vibration-measuring test (LTV test)

The LTV test has been conducted since 14 August 2006, to evaluate the seasonal changes of the natural frequencies, where the modal property varies with temperature or reservoir water level. For this test, two tri-axial accelerometers are installed on the right-hand-side (sensor A) and the center (sensor B) of the dam crest as shown in Figure 1, to avoid nodes as ‘zero’ displacement points, and to obtain the cross-spectrum of the responses among the two measuring points. The measurement system was configured to record continuously with the sampling rate of 200Hz and the measuring data is stored in every one hour. Six thermometers are also set on the upstream and downstream surfaces of the dam respectively, as shown in Figure 1.

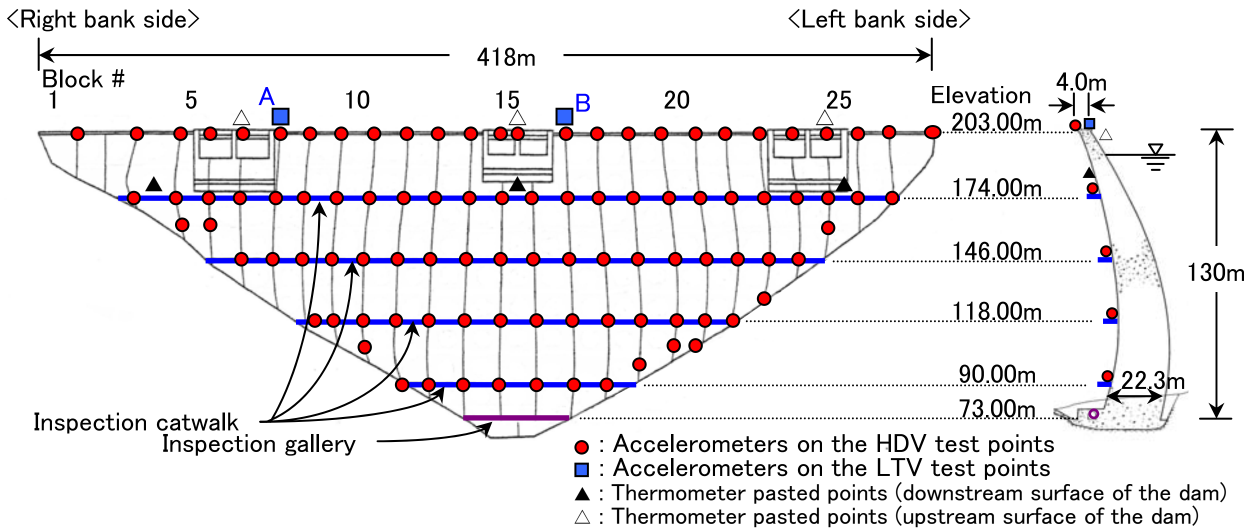


Figure 1 The shape of the dam and measuring points of two kinds of ambient vibration tests

4.EVALUATION OF THE PRESENT DYNAMIC PROPERTIES

The relation between the natural frequency and the mode shape of the dam was analyzed using the HDV test data, and the change for about one year of the natural frequency is obtained from the LTV test data. Hereafter, the detail of each test result is described in each subsection.

4.1. Identification of mode shapes (the HDV test results)

Figure 2 shows the auto power spectral density function (PSD) curves obtained from the data measured by the sensors A and B (measuring on the LTV test) on the day of the HDV test. Applying the identification method based on cross spectrum to the HDV test data, three mode shapes can be identified as shown by the lower triangle marks in Figure 2. Figure 3 illustrates the identified three mode shapes. The Mode 1 is the First anti-symmetric mode, the Mode 2 is the second symmetric mode, and the Mode 3 is the second anti-symmetric mode. As shown in each mode shape, it is confirmed that the deformation shapes on the every height of the dam are almost the same but its amplitudes decrease with the lower height. These three mode shapes are almost the same as the mode shapes which are obtained by the past forced vibration test conducted 42 years ago [8]. It is also shown that the ambient vibration measurement gives the accurate mode shapes comparable to the results by the forced vibration test. However, we cannot directly compare the present results with those of the past one at 42 years ago, because both water levels are different from each other; they are 179.20m at present, 200.00m in the past. The comparison with considering the change of water level will be discussed in the subsection 4.3.

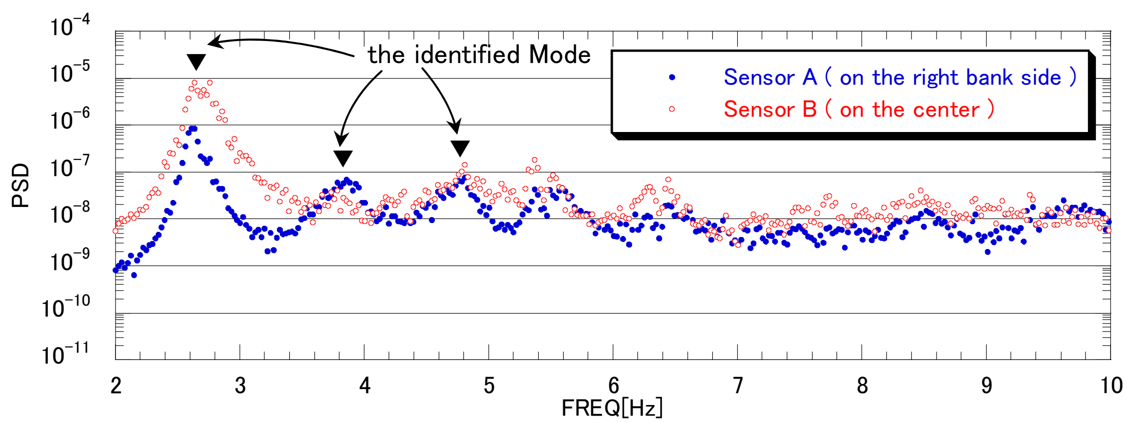
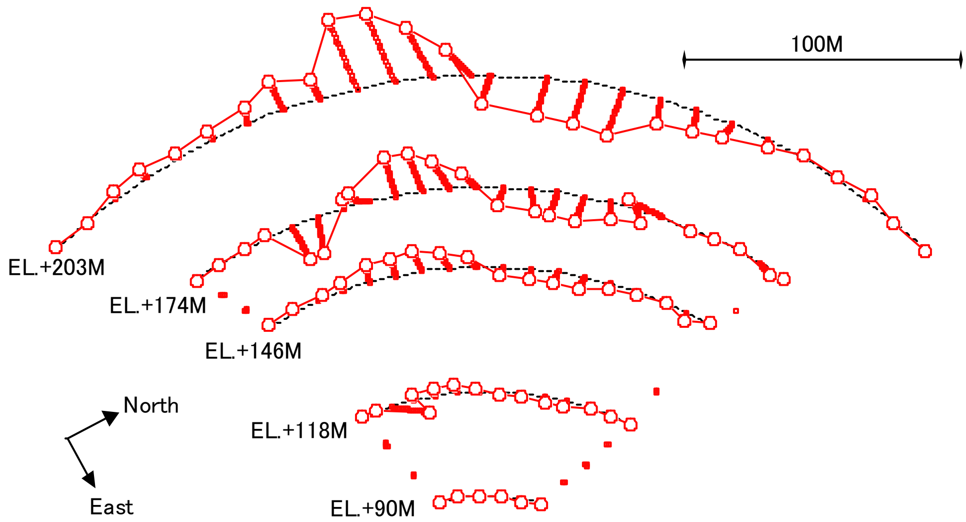
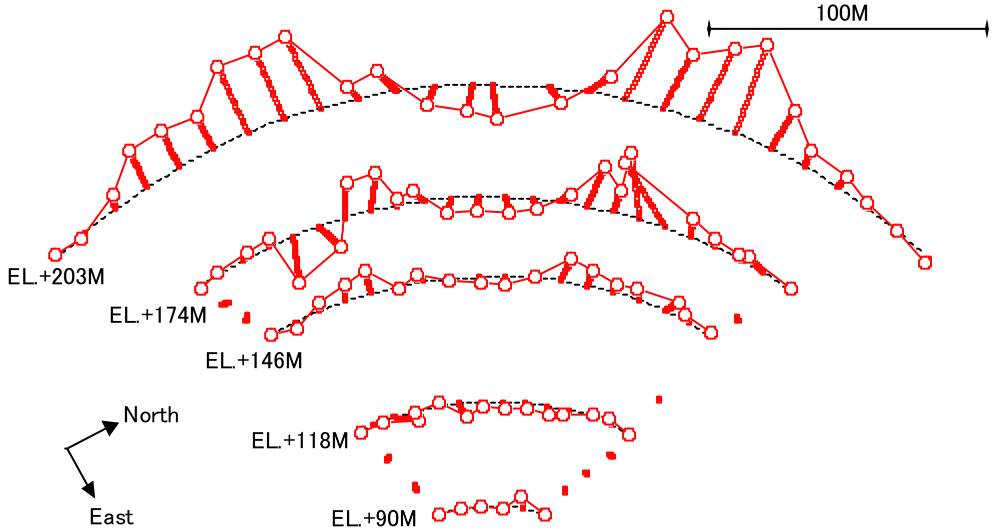


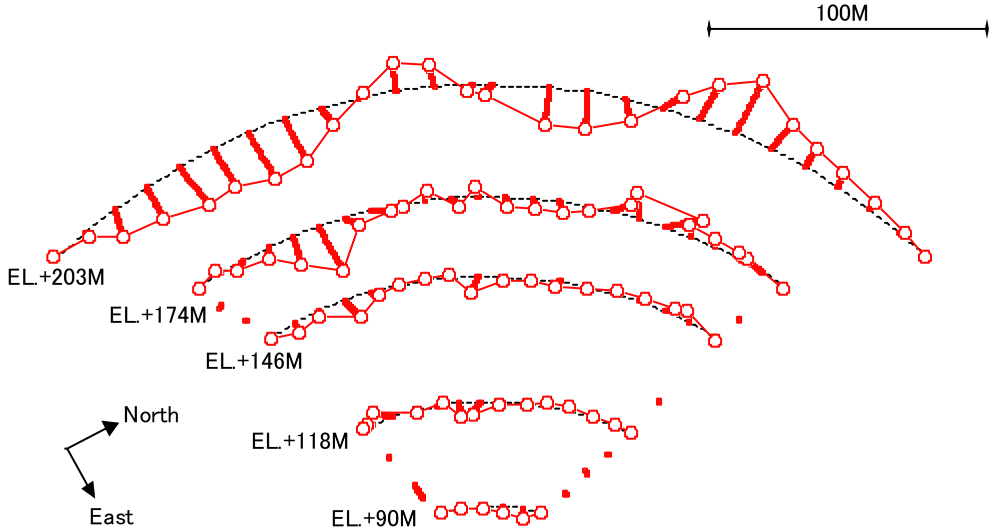
Figure 2 Power spectral density curves on the day of the HDV test



(a) Mode 1 (2.58-2.8 Hz) [First anti-symmetric mode]



(b) Mode 2 (3.8-4.0 Hz) [Second symmetric mode]



(c) Mode 3 (4.6-4.8 Hz) [Second anti-symmetric mode]

Figure 3 Identified the lowest three mode shapes

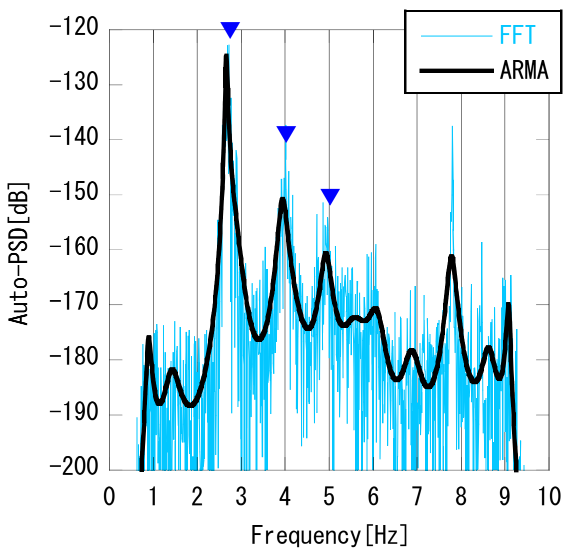
4.2. The LTV test results

The authors investigate seasonal changes of the natural frequencies identified from the LTV test data. The natural frequencies are identified for every 5 minuets by applying the identification method based on ARMA model, where velocity data is employed which are obtained by integrating the measured acceleration records. Figure 4 shows the PSD when water levels are the lowest and highest which are calculated in the system identification process as well as the result by Fast Fourier Transform (FFT). The resonance peaks of the lowest three modes are dominant at the lowest water level whereas it is inferior at the highest water level. In this analysis, the velocity data is used to obtain the lower three natural frequencies accurately, which can emphasize the lower frequency components than the acceleration can.

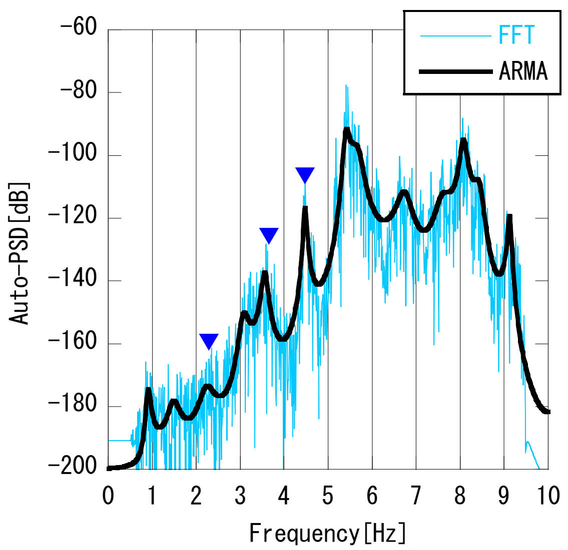
Figure 5 shows the time histories of natural frequencies, with the reservoir water level, dam temperature, and the root-means-square of the velocity response for about one year or more. To compare the natural frequencies with varying the reservoir water level as shown in Figures 5(a) and (d), we found strong correlations between reservoir water level and natural frequencies. Especially for the period from July to September 2007, the natural frequencies rapidly decrease as the water level rises, and vice versa. Details of the relation between the water level and the natural frequency will be discussed in the subsection 4.3.

From the temperature and the natural frequency as shown in Figures 5(b) and (d), we found another correlation. That is, we found that the slow change of natural frequencies (varying monthly) corresponds with the temperature change of the dam surface. And the change of the natural frequencies within short time interval is also found to be corresponding with the daily change of dam surface temperature.
However, it is difficult to divide the changes of the natural frequency due to water level and temperature completely, because both water level and temperature are also correlated with each other. To clarify these correlations, further investigations are needed.

Figure 5(c) shows the responses of the dam observed with the sensor B (placed on the crest center of the dam). There is no substantial change in the fluctuation band of the response except for the three months including from July to September, 2007. In this period, heavy rains fell around the dam site and the reservoir water of the dam is released from spillway gates.

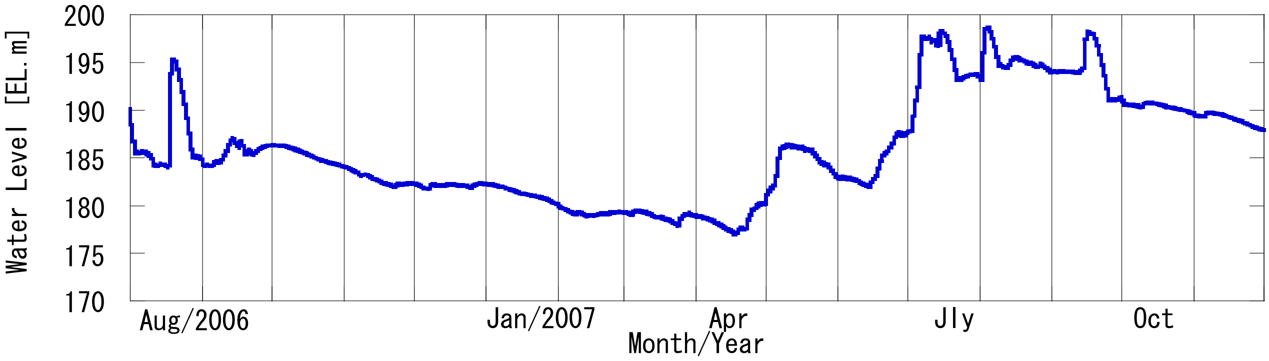


(a) At the lowest water level (EL.176.94 m)

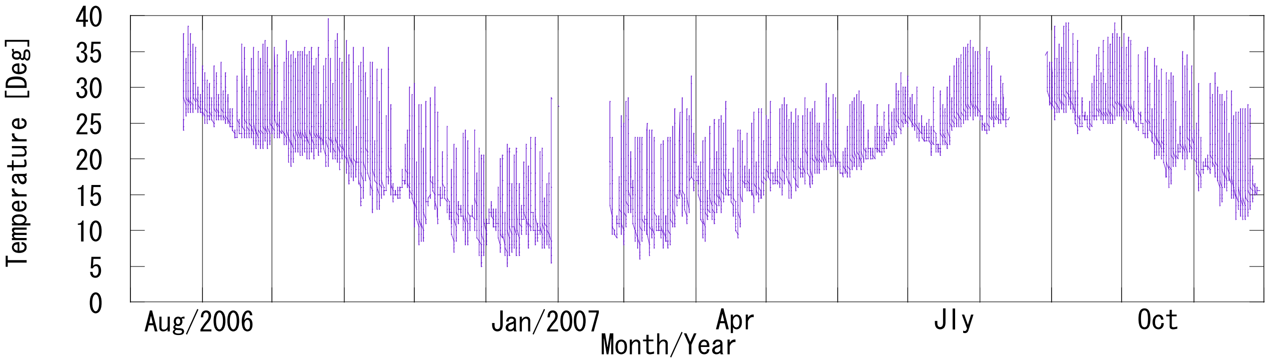


(b) At the highest water level (EL.198.66 m)

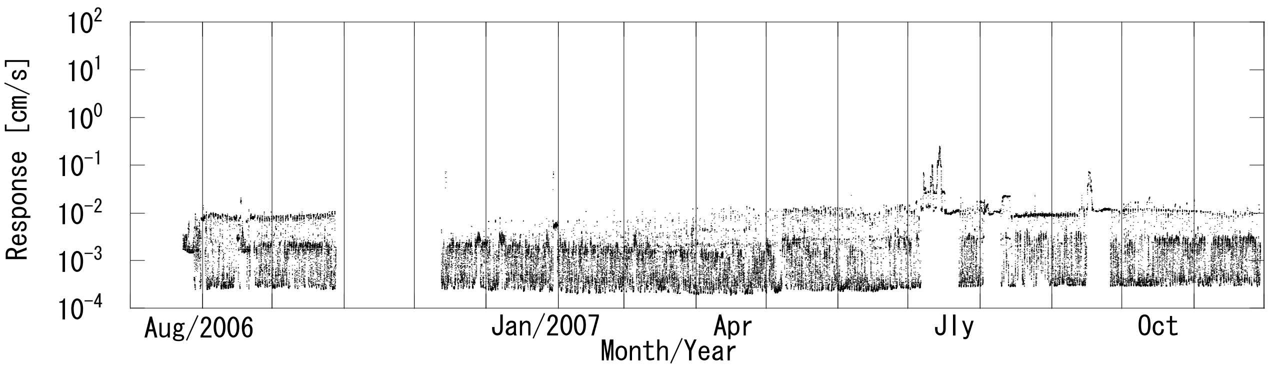
Figure 4 The PSD at the lowest and highest water level of measuring period



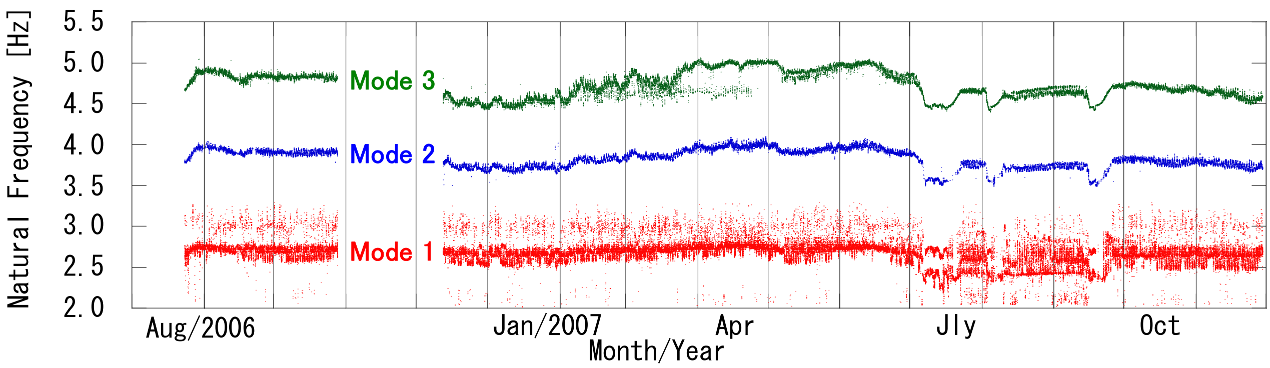
(a) Reservoir water level



(b) Temperature at the downstream surface of the dam



(c) Response



(d) Natural frequencies

Figure 5 The time histories of water level, dam temperature, response, and natural frequencies

4.3. Reservoir water level effects

Figure 6 shows the variations of the natural frequencies versus the reservoir water level for the lowest three natural frequencies. The scattering band of the frequencies of the Mode 1 (1st anti-symmetric mode) is larger than that of other two modes. This reason is that there might exist two close modes in frequency, one is the 1st anti-symmetric mode shown in the Figure 3(a), the other is the 1st symmetric mode which cannot be identified individually from the LTV record. However, the Mode 2 (2nd symmetric) and the Mode 3 (2nd anti-symmetric modes) can be identified very clearly.

Now, we will discuss about the natural frequencies effects on the reservoir water level: in all modes when the reservoir water level rises from the lowest to a certain level (up to 180.00m), natural frequencies slightly increase with increasing the water level (as shown in Figure 6). This behavior can be attributed to the increase of the stiffness of the dam concrete due to the contraction along the construction joints under increasing hydrostatic pressure. After the water level reached above 180.00m or more, the added mass effect of the reservoir becomes dominant and the natural frequencies begin to decrease with increasing water level. The characteristic of frequencies with increasing water level was also reported on the Contra, Emosson, Mauvoisin arch dams in Switzerland by the forced vibration test and the ambient vibration test [3][4].

In Figure 6 also plotted are the natural frequencies identified by FFT from seven small earthquake observation data recent recorded by other seismometers. Though from these earthquake observation data, only the first and the second natural frequencies could be identified, the natural frequencies identified from the earthquake records are in good agreement with those obtained from the LTV tests.

Throughout these results, it is confirmed that the two ambient vibration tests can evaluate the accurate natural frequencies of large arch dam, instead of evaluations by seismic records or forced vibration test. In addition, it can be said that the LTV test data has the advantages, which can evaluate the accurate natural frequencies for various water levels, and it is possible to apply to develop the structural damage detection method [2][7].

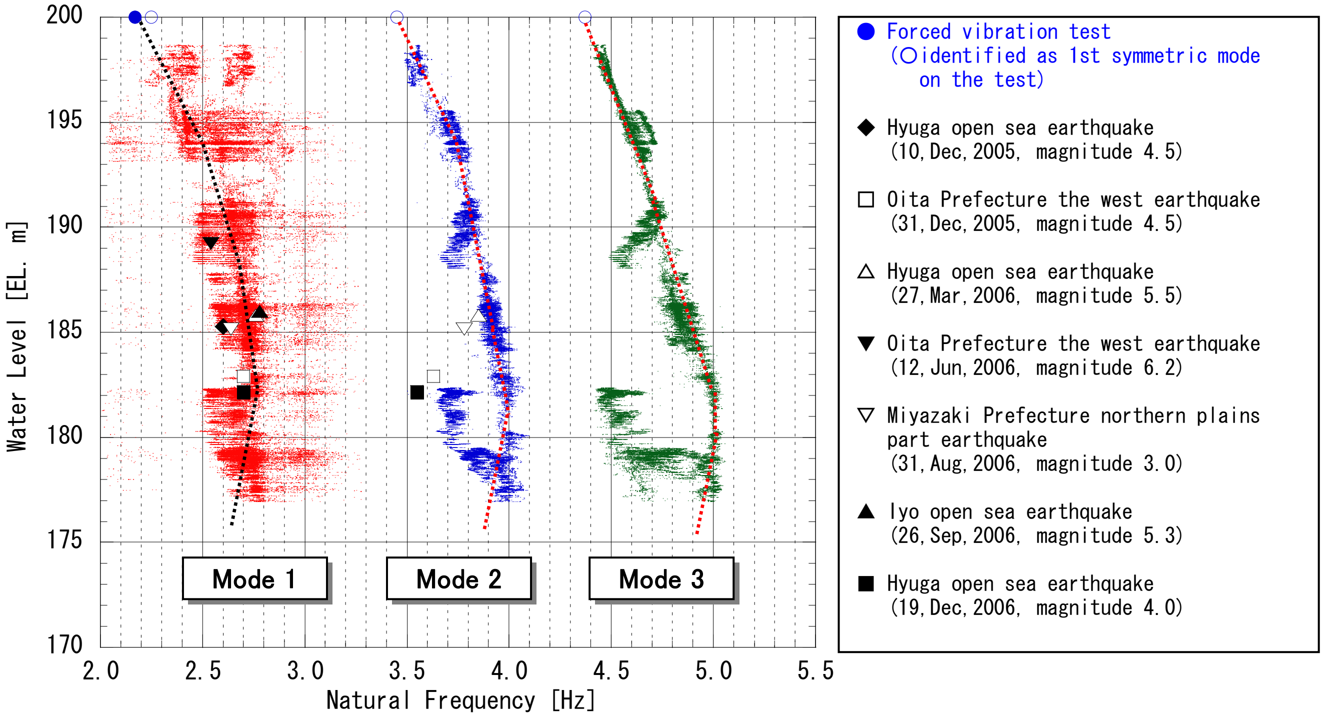


Figure 6 Effect of reservoir water level on resonant natural frequencies

5.COMPARISON WITH THE TEST OF 42 YEARS AGO

On the HDV test, the lowest three mode shapes can be identified in the present states of the dam. We found the identified three mode shapes are the same as those obtained from the forced vibration test conducted 42 years ago [8]. However, the water levels in the present HDV test and the past forced vibration test are different. Considering the water level, the natural frequencies are compared both in the present and the past states, as follows.

Figure 6 also are plotted the natural frequency identified from the past forced vibration test of 42 years ago. The past test was carried out for the highest water level (EL.200.00m), and the LTV test has not been obtained for the water level of EL.200.00m yet, because the highest water level is EL.198.66m of the LTV test can be up to now. However, Figure 6 shows that this resonance point identified from the past test is estimated from the regression curve drawn from the natural frequencies identified from the LTV test. Even by the immediate comparison, it is possible to conclude that natural frequencies have not changed for 42 years.

6.CONCLUSION

From the two kinds of ambient vibration test of the high-density vibration array test (the HDV test) and the long-term continuous vibration-measuring test (the LTV test), we could evaluate the lowest three mode shapes, the seasonal change of natural frequency, and the change of natural frequency due to the water level change. These results are compared with the past forced vibration test results and the earthquake observation records in the recent years. As a result, we concluded that the natural frequencies of these identified three modes strongly correlated with the water level of the dam, and these identified natural frequencies are in good agreement with those obtained from recent earthquake records. And the present natural frequencies have not changed for 42 years. These present dynamic properties will be employed for calibrating a finite element model of the dam-foundation rock-reservoir water interaction system for earthquake response analysis, as well as used as the fundamental data for developing structural damage detection based on ambient vibration test.

REFERENCES

1. Kenji Kanazawa. (2004). Application of cross spectrum based modal identification to output-only records of ambient vibration. *The 13th World Conference on Earthquake Engineering 2004;3068*
2. Kenji Kanazawa. (2006). Structural damage detection from natural frequency eliminated by temperature effect. *The 24th International Modal Analysis Conference (IMAC);No.90*
3. Jean Proulx, Patric Paultre, et al., (2001). An experimental investigation of water level effects on the dynamic behavior of a large arch dam. *Earthquake Engineering and Structural Dynamics 2001;30:1147-1166*
4. Georges R. Darbre, Jean Proulx. (2002). Continuous ambient-vibration monitoring of the arch dam of Mauvoisin. *Earthquake Engineering and Structural Dynamic 2002;31:475-480*
5. Kenji Kanazawa. (2002). Structural damage detection based on ambient vibration measurements (Part. II) - ARMAMA Model for Spectrum Analysis - . *Central Research Institute of Electric Power Industry Report U01031*
6. Kenji Kanazawa. (2002). Structural damage detection based on ambient vibration measurements (Part. III) - Modal and Structural Identification of Multi-story Building using ARMAMA model - . *Central Research Institute of Electric Power Industry Report U01046*
7. Kenji Kanazawa. (2006). Structural damage detection based on ambient vibration measurements (Part. IV) - Long-term modal parameter transition from two-years vibration records - . *Central Research Institute of Electric Power Industry Report N05025*
8. Tadashi Takahashi, Hajime Tsutsumi, et al., (1966). About the forced vibration test of Hitotsuse arch dam. *Central Research Institute of Electric Power Industry Report 66017*