The comparison between the acquisition vibration data obtained by different types of transducers for hydraulic turbine head cover

LI Youping¹, LU Jinsong², CHENG Jian¹, YIN Yongzhen¹ and WANG Jianlan¹
¹ Technology and Research Center of China Yangtze Power Corporation, Yichang Hubei,443002, P.R.China
² XiangJiaBa Hydraulic Power Plant, Yibin, Sichuan 644000, P.R.China

Abstract. Based on the summaries of the rules about the vibration measurement for hydro-generator sets with respect to relevant standards, the key issues of the vibration measurement, such as measurement modes, the transducer selection are illustrated. In addition, the problems existing in vibration measurement are pointed out. The actual acquisition data of head cover vertical vibration respectively obtained by seismic transducer and eddy current transducer in site hydraulic turbine performance tests during the rising of the reservoir upstream level in a certain hydraulic power plant are compared. The difference of the data obtained by the two types of transducers and the potential reasons are presented. The application conditions of seismic transducer and eddy current transducer for hydro-generator set vibration measurement are given based on the analysis. Research subjects that should be focused on about the topic discussed in this paper are suggested.

1. Introduction

1.1. Evaluation of vibration
The level of mechanical vibration can be expressed by displacement, velocity or acceleration, in which the displacement reflects the amplitude, the velocity reflects the energy and the acceleration reflects the impact force. It can also be considered that the level of vibration is in proportion to the displacement while the frequency of vibration is low, to the velocity while the frequency is medium and to the acceleration while the frequency is high. Therefore, the peak-peak value of displacement is measured for low speed (less than 300 rpm) machines, the root mean square value of speed is measured for medium and high speed (300 rpm ~ 1800 rpm) machines.

1.2. Character of hydro-generator vibration
Generally, the rotational speed of hydro-generators is relatively low, which is about 1 ~ 2 Hz for large and medium capacity hydro-generators. The vibration caused by the vortex in draft tube cone is lower, which is about 1/6 ~ 1/2 times of the rotational frequency. Because the hydraulic factor has a great influence on the head cover, the frequencies of head cover vibration are mostly low components. It is widely believed that the measurement results of head cover vibration are not accurate enough.
1.3. Measurement mode for hydro-generator vibration

There are two types of transducers to measure hydro-generator vibration. Contacting transducers are usually used to measure the absolute vibration for non-rotational components, such as bearing seats and brackets. Seismic transducers are generally used as contacting transducers. Non-contacting transducers can be fixed to rigid mounting brackets and applied to measure directly the vibration displacement when the vibration of the mounting brackets can be ignored. Eddy current transducers are commonly used as non-contacting transducers.

1.4. Demands of hydro-generator vibration measurement devices

The frequency response range of vibration measurement devices for Francis is specified by IEC 994 as following[2]. lower frequency of measurement device frequency response \( f_l \) and the upper frequency of measurement device frequency response range \( f_u \) should be according to equation (1) and equation (2).

\[
\begin{align*}
\frac{f_l}{f_p} &= 0.1 \times f_p \\
\frac{f_u}{f_l} &= \max \left\{ z_0 \times z_1 \times f_p, Sh \times V_w \times \delta^{-1} \right\}
\end{align*}
\]

Where, \( f_p \) is rotational frequency of hydro-generator at specified speed, \( z_0 \) is number of guide vanes, \( V_w \) is flow velocity, \( \delta \) is thickness of outlet edge of a hydraulic profile (guide vane, runner blade, etc), \( Sh \) is Strouhal number, \( z_1 \) is number of runner blades.

1.5. Transducers for hydro-generator vibration measurement

The rated rotational speed of some large capacity hydro-generators in the world are listed in Table 1. Because of the limitation of technology and craftsmanship, the bandwidth of the seismic transducers at present is difficult to meet the demands of the lower limit mentioned above.

| Plant                      | Manufacturers | Rated Output (MW) | Rated Speed (rpm) | 0.1\( \times \) Rotational Frequency (Hz) |
|----------------------------|--------------|------------------|------------------|------------------------------------------|
| Right Bank and Underground of Three Gorges Plant | DEC          | 700              | 75.0             | 0.13                                     |
| XiluoDu Plant              | ALSTOM       | 700              | 71.4             | 0.12                                     |
| XiangJiaBa Plant           | HEC          | 700              | 75.0             | 0.13                                     |
| Grand Coulee III Plant     | ALSTOM       | 800              | 71.4             | 0.12                                     |
| Itaipu Plant               | HEC          | 800              | 75.0             | 0.13                                     |
| Raul Leoni II Plant        |              | 600              | 112.5            | 0.19                                     |

The key feature of the eddy current transducer is that it can accurately measure the static and dynamic distances between the measured metal and the probe of the transducer[3]. Additionally, it is provided with the performance of zero frequency response and can be used to measure the hydro-generator vibration with low frequency components. The main problem lies in the erection difficulty of the mounting brackets of the transducers. Furthermore, the vibration of the mounting bracket is inevitable, which will adversely affect the measure results when the eddy current transducer is used to measure the vibration. In a stability and performance test for a certain hydro-generator, contacting seismic transducers and non-contacting eddy current transducers were used to measure the head cover vibration. The acquisition vibration data respectively obtained by the two types of transducers in the tests are compared and the influence of the transducer type on measurement result is analyzed in this paper.
2. Parameters of the hydro-generator and the test conditions

2.1. Hydro-generator parameters
The hydro-generator’s rated power is 770 MW, its rated speed is 125 rpm, its rated water head is 197 m. The maximum diameter of the head cover is 11 m, and the runner has 15 blades.

2.2. Test conditions
Stability and performance tests were carried out under 23 water heads while the gross water heads changed from 175 m to 215 m.

2.3. Transducer features
The nominal frequency response range of the seismic transducer is 0.35 Hz to 200 Hz, the nominal span range is ±1000 μm and the nominal sensitivity is 8 mv/μm. The characteristic curve calibrated in factory acceptance test is shown as figure 1. It can be seen that the vibration response of the transducer is stable while the vibration frequency is exceeding 0.5 Hz, and is degenerative while the vibration frequency of is less than 0.5 Hz.

![Figure 1](image)

**Figure 1** characteristic curve of seismic transducer

The nominal span range of the eddy current transducer is 1.5 mm to 3.5 mm and the nominal sensitivity is 8 mv/μm. The characteristic curve of the transducer is shown as figure 2.
2.4. Transducer installations

Seismic transducers were installed in the direction of +X and +Y of the head cover inner side, the eddy current transducer is installed close to the direction of +X (shown as figure 3). The mounting bracket of the eddy current transducer consisted of several steel pipes. One end of the pipes were welt to the pit liner and the other ends were hanged in the air. The impending ends of the pipes were connected together by a short steel pipe (shown as figure 4).

Figure 2  characteristic curve of eddy current transducer

Figure 3  erection of transducers
3. Test data analysis

3.1. Acquisition vibration data

The data obtained by seismic transducers and eddy current transducers are shown in figure 5 and figure 6 respectively.

The vibration data of head cover obtained under different output conditions with typical gross water heads of 214.7 m, 198.2 m and 183.3 m are selected to be compared. The vibration peak-peak values are listed in Table 2, the 1st to 4th main frequencies and the corresponding amplitudes of the head cover vertical vibration are listed in Table 3 to Table 5 respectively.
**Figure 6**  vertical vibration of head cover (obtained by eddy current transducer)

**Table 2** vertical vibration peak-peak value of head cover under representative heads

| Vibration (μm) H=214.7 m | Vibration (μm) H=198.2 m | Vibration (μm) H=183.8 m |
|--------------------------|--------------------------|--------------------------|
| **Output (MW)**          | **Seismic Transducer** | **Eddy Current Transducer** | **Output (MW)** | **Seismic Transducer** | **Eddy Current Transducer** | **Output (MW)** | **Seismic Transducer** | **Eddy Current Transducer** |
| 767                      | 14                       | 18                       | 766                      | 40                       | 45                       | 696                      | 26                       | 26                       |
| 755                      | 13                       | 16                       | 756                      | 36                       | 38                       | 673                      | 16                       | 22                       |
| 747                      | 13                       | 16                       | 740                      | 25                       | 29                       | 645                      | 12                       | 15                       |
| 743                      | 12                       | 16                       | 726                      | 18                       | 27                       | 621                      | 12                       | 15                       |
| 735                      | 12                       | 16                       | 715                      | 14                       | 18                       | 595                      | 11                       | 15                       |
| 724                      | 12                       | 16                       | 706                      | 12                       | 19                       | 573                      | 11                       | 14                       |
| 715                      | 12                       | 15                       | 697                      | 12                       | 20                       | 546                      | 13                       | 17                       |
| 703                      | 12                       | 16                       | 669                      | 12                       | 22                       | 526                      | 15                       | 30                       |
| 694                      | 12                       | 15                       | 646                      | 11                       | 14                       | 496                      | 19                       | 25                       |
| 669                      | 12                       | 15                       | 621                      | 11                       | 16                       | 449                      | 20                       | 39                       |
| 641                      | 12                       | 16                       | 594                      | 11                       | 15                       | 398                      | 30                       | 44                       |
| 619                      | 14                       | 19                       | 570                      | 14                       | 39                       | 299                      | 34                       | 43                       |
| 595                      | 19                       | 23                       | 546                      | 20                       | 25                       | 200                      | 59                       | 65                       |
| 569                      | 20                       | 25                       | 520                      | 18                       | 23                       | 99                       | 67                       | 61                       |
| 547                      | 21                       | 27                       | 499                      | 17                       | 21                       |                        |                       |                       |
| 521                      | 18                       | 23                       | 446                      | 21                       | 29                       |                        |                       |                       |
| 493                      | 22                       | 28                       | 394                      | 33                       | 45                       |                        |                       |                       |
| 473                      | 24                       | 33                       | 296                      | 20                       | 28                       |                        |                       |                       |
| 447                      | 28                       | 38                       | 196                      | 51                       | 66                       |                        |                       |                       |
| 394                      | 32                       | 42                       | 99                       | 42                       | 45                       |                        |                       |                       |
| 296                      | 35                       | 39                       |                        |                       |                       |                        |                       |                       |
| 195                      | 86                       | 61                       |                        |                       |                       |                        |                       |                       |
| 97                       | 52                       | 46                       |                        |                       |                       |                        |                       |                       |

**Table 3** 1st~4th main frequencies and the corresponding amplitudes as H=214.7 m

| Output (MW) | Vibration +X(Seismic Transducer) | Vibration(eddy current transducer) |
|-------------|----------------------------------|------------------------------------|
| 767         | 1st Amp 1st Frequency (Hz) 3.123 | 1st Amp 1st Frequency (Hz) 3.123 |
| 767         | 2nd Amp 2nd Frequency (Hz) 0.39 | 2nd Amp 2nd Frequency (Hz) 0.39 |
| 767         | 3rd Amp 3rd Frequency (Hz) 0.52 | 3rd Amp 3rd Frequency (Hz) 0.52 |
| 767         | 4th Amp 4th Frequency (Hz) 1     | 4th Amp 4th Frequency (Hz) 1     |

| Output (MW) | Vibration +X(Seismic Transducer) | Vibration(eddy current transducer) |
|-------------|----------------------------------|------------------------------------|
| 2.08        | 1st Amp 1st Frequency (Hz) 3.123 | 1st Amp 1st Frequency (Hz) 3.123 |
| 2.08        | 2nd Amp 2nd Frequency (Hz) 0.39 | 2nd Amp 2nd Frequency (Hz) 0.39 |
| 2.08        | 3rd Amp 3rd Frequency (Hz) 0.52 | 3rd Amp 3rd Frequency (Hz) 0.52 |
| 2.08        | 4th Amp 4th Frequency (Hz) 1     | 4th Amp 4th Frequency (Hz) 1     |
Hyperbole
IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series 813 (2017) 012039
doi:10.1088/1742-6596/813/1/012039

Table 4 1st-4th main frequencies and the corresponding amplitudes as H=198.2 m

| Output (MW) | Vibration +X(Seismic Transducer) | Vibration(EDDY current transducer) |
|-------------|----------------------------------|-----------------------------------|
|             | 1st Fre: 1st main frequency      | 3rd Fre: 3rd main frequency       |
|             | Amp 1st: Amplitude of 1st main frequency | Amp 3rd: Amplitude of 3rd main frequency |
|             | 2nd Fre: 2nd main frequency      | 4th Fre: 4th main frequency       |
|             | Amp 2nd: Amplitude of 2nd main frequency | Amp 4th: Amplitude of 4th main frequency |
| 766         | 0.97 12 1.09 9 0.85 7 1.01 6     | 0.02 13 0.97 10 1.09 8 1.01 6    |
| 756         | 1.04 7 1.18 7 0.96 5 0.98 5      | 0.02 8 1.04 6 1.18 6 0.96 5     |
| 740         | 2.36 4 1.11 4 1.27 4 1.19 3     | 13.20 6 1.11 3 13.22 3 1.27 3   |
| 726         | 2.08 3 0.95 2 31.22 2 1.23 2     | 28.63 5 17.64 5 13.20 5 17.62 4 |
| 715         | 2.08 3 31.23 2 18.78 1 1.13 1     | 2.08 3 14.69 2 31.23 2 13.22 2  |
| 706         | 2.08 3 31.23 2 0.32 1 0.53 1     | 0.02 7 2.08 3 0.04 3 31.23 2    |
| 697         | 2.08 3 31.23 2 18.80 1 0.22 1     | 0.02 6 28.62 4 2.08 3 0.04 3    |
| 669         | 2.08 3 31.23 2 18.84 1 0.40 1     | 0.02 13 2.08 3 0.04 2 31.23 2   |
| 646         | 2.08 3 31.22 2 18.86 1 14.98 1     | 2.08 3 28.62 2 31.22 2 14.69 2  |
| 621         | 2.08 2 31.22 2 18.89 1 0.32 1     | 0.02 3 2.08 3 0.04 3 14.69 2    |
| 594         | 2.08 2 18.73 2 31.22 2 15.01 1     | 28.61 3 2.08 3 18.73 2 14.69 2  |
| 570         | 0.46 4 2.08 2 18.94 2 0.44 2     | 0.02 28 0.04 5 0.46 5 0.08 4    |
| 546         | 0.44 7 0.48 2 2.08 2 1.09 2     | 0.44 7 0.24 4 0.20 3 0.48 3    |
| 520         | 0.53 8 1.05 4 1.03 3 0.51 2     | 0.53 10 1.05 4 1.03 3 1.56 3   |
| 499         | 0.53 7 1.05 5 1.58 2 0.42 1     | 0.53 9 1.05 6 1.58 2 13.22 2   |
| 446         | 0.53 4 1.37 3 1.11 2 0.51 2     | 0.53 5 0.28 5 0.34 4 0.02 3    |
| 394         | 0.46 15 0.49 7 0.44 6 0.95 5     | 0.46 18 0.49 9 0.44 7 0.95 5   |
| 296         | 0.73 3 0.42 3 0.79 2 0.36 2     | 0.06 5 0.32 4 0.28 3 0.73 3    |
| 196         | 0.34 12 0.32 6 0.55 6 0.53 5     | 0.02 16 72.88 8 17.65 6 0.06 6  |
| 99          | 0.36 7 0.28 6 0.20 6 0.53 6     | 0.10 5 0.32 5 0.04 5 0.26 5    |

Table 5 1st-4th main frequencies and the corresponding amplitudes as H=183.3 m
### Data analyses

1) Based on the comparison between figure 5 and figure 6, it can be seen,

① For the head cover vibrations obtained by the two types of transducers, there both exist two peaks when the output is near 200 MW and 400 MW respectively under different water heads. The main frequencies of the vibration at the two peaks are $1/6 \sim 1/2$ times of the rotational frequency (2.08 Hz) and are typical vortex frequency components. Low extreme point of the head cover vibration occurs when the output is within 600 MW~700 MW. The head cover vibration increases sharply with the increasing of the output after the low extreme point, the output at the low extreme point increases with the increasing of water head.

The reasons causing the above-mentioned phenomena are detailed as follow. The circumferential component in the runner outlet is minimum at the low extreme point and the runner is under zero circumferential component condition. At this point, the pressure fluctuation reaches the minimum and hence the vibration of the head cover reaches the minimum. The circumferential component in the runner outlet increases with the increasing of the guide vane opening or the output. In this case, the pressure fluctuation increases, which results in the dramatic increasing of the head cover vibration. On the other hand, the output at the zero circumferential component condition increases with the increasing of the water head. Consequently, the output at the low extreme point of the head cover vibration increases with the increasing of the water head.

According to ① and ②, the peak-peak values of head cover vibration obtained by seismic transducer and eddy current transducer can both correctly reflect the vibration variation with the water head and output.

2) It can be seen from Table 2,

① The peak-peak values of head cover vibration obtained by the two types of transducers are well-matched in general under high output (when the output exceeds 500 MW) conditions. The differences between the data obtained by the two types of transducers are less than 10 μm and the data obtained by seismic transducers are generally less than that obtained by eddy current transducers.

The possible reasons are as following. The main frequency components of head cover vibration are no longer low vortex frequency under large output conditions as the large output conditions are far away from vortex conditions. The head cover vibration frequency components under these conditions are within the stable measurement frequency range of the seismic transducer. As for the eddy current transducer, the vibration of the mounting bracket itself is inconspicuous under such condition and has less influence on the obtained data of the

| Output (MW) | Vibration +X (Seismic Transducer) | Vibration (eddy current transducer) |
|-------------|-----------------------------------|-------------------------------------|
|             | 1st Amp (μm) | 2nd Amp (μm) | 3rd Amp (μm) | 4th Amp (μm) | 1st Amp (μm) | 2nd Amp (μm) | 3rd Amp (μm) | 4th Amp (μm) |
| 696         | 1.04        | 1.11        | 1.24        | 1.06        | 13.19       | 4.04        | 4.01        | 4.12        |
| 673         | 2.08        | 1.86        | 2.12        | 1.29        | 28.58       | 4.08        | 4.01        | 4.12        |
| 645         | 2.08        | 0.30        | 1.31        | 0.38        | 28.61       | 3.08        | 3.08        | 4.12        |
| 621         | 2.08        | 1.87        | 1.31        | 1.29        | 2.08        | 3.08        | 3.08        | 4.12        |
| 595         | 2.08        | 1.87        | 1.31        | 1.29        | 14.69       | 3.08        | 3.08        | 4.12        |
| 573         | 2.08        | 1.88        | 1.31        | 1.29        | 28.63       | 3.08        | 3.08        | 4.12        |
| 546         | 0.48        | 2.08        | 0.45        | 2.18        | 0.48        | 2.08        | 0.45        | 2.18        |
| 526         | 0.43        | 0.45        | 2.18        | 0.50        | 0.02        | 7.03        | 0.04        | 7.08        |
| 496         | 0.55        | 1.07        | 0.53        | 0.25        | 0.55        | 1.08        | 0.53        | 0.30        |
| 476         | 1.09        | 0.79        | 0.53        | 1.32        | 0.02        | 9.09        | 0.03        | 9.08        |
| 498         | 0.49        | 0.51        | 0.81        | 0.30        | 0.49        | 0.50        | 0.81        | 0.32        |
| 299         | 0.49        | 0.99        | 0.64        | 0.53        | 0.49        | 0.16        | 0.34        | 0.46        |
| 200         | 0.36        | 0.33        | 0.61        | 0.28        | 0.02        | 11.82       | 0.28        | 11.82       |
| 99          | 0.22        | 0.24        | 0.49        | 0.29        | 0.02        | 15.82       | 0.28        | 15.82       |
head cover vibration. Therefore, the two types of transducers can both measure the head cover vibration stably under large output conditions. At the same time, as the vibration of the mounting bracket is unavoidable, the data obtained by eddy current transducers are slightly greater than that obtained by seismic transducers.

1. The data obtained by the two types of transducers have larger differences under low output conditions (when output is less than 400 MW). The difference is 25 μm under the condition of H=214.7 m and P=195 MW. There is no obvious regularity of the quantity relationship between the data obtained by the two types of transducers.

The possible reasons are as following. The main frequency components of the head cover vibration are relatively small under the low output conditions. The attenuation of the vibration with different low frequencies obtained by the seismic transducer are not the same, which may result in the reduction of the measurement stability of the seismic transducer. For the eddy current transducer, as the vibration of the hydro-generator is large under the low output conditions, the vibration transmitted from the pit liner to the mounting bracket is relatively large and the data obtained by eddy current transducers are of poor stability.

3) It can be seen from Table 3 to Table 5,

5. The main frequency components and the corresponding amplitudes of the head cover vibration obtained by the two types of transducers are quite same under medium and large output conditions (when output is larger than 400 MW), and they can both reflect the characteristic frequencies of Francis turbine, such as the vortex frequency components, rotational frequency component, product of rotational frequency and number of runner blades.

6. The similarity of the main frequency components of the head cover vibration obtained by the two types of transducers is small under the low output conditions (when output is less than 400 MW), the data obtained by seismic transducer can reflect the vortex frequency components. But the data obtained by eddy current transducer can not. The correlation between the vibration frequencies obtained by the eddy current transducer and known hydraulic turbine characteristic frequencies is not strong. However, the main frequency components of the vibration obtained by the eddy current transducer under different water heads are similar in general, which probably results from the inherent frequency of the mounting bracket or the vibration transmitted from the pit liner.

3.3. Summary

The above-mentioned analyses indicate that,

1) The measure results obtained by seismic transducers are comparatively accurate when the main frequency components of the hydro-generators vibration are within the stable frequency response range of the transducer. Therefore, seismic transducers can be applied in the vibration measurement when the rotational frequency exceeds 4～6 times of the low limit of the stable frequency response range.

2) The measurement results obtained by eddy current transducers are comparatively accurate when the vibration of the mounting bracket is small. The deviation between the measurement result and the actual vibration is significant when the vibration of the mounting bracket is obvious.

4. Conclusions

The actual head cover vibration data obtained by seismic transducers and eddy current transducers are compared in this paper. It is pointed out that the hydro-generator vibration can be correctly measured by both the two types of transducers under certain conditions, and the suitable conditions for the two types of transducer are pointed out also. Because of some limitations of the instance in the paper, the influence research of the transducer type on the measurement results of hydro-generator vibration is not sufficiently comprehensive. The following aspects on this subject can be further studied:

1) As the runner rotational speed measured in this paper is quite high, the effect of the seismic transducer being applied in the vibration measurement for lower rotational speed of
the hydro-generator has not been verified. Therefore, the subsequent research can be carried out aiming at the hydro-generators with lower rotational speed.

2) The inherent frequency of the eddy current mounting bracket and the vibration transmitted from the pit liner are not measured in the instance while using eddy current transducer to measure the vibration. As a result, the vibration of the mounting bracket are not deducted from the measurement results, which should be taken into account in the subsequent tests and researches.

3) Some other types of transducers, such as fiber optic transducers, are presently being used to measure the vibration of rotational machines[7]. The application of such transducers in the vibration measurement of hydro-generators, as well as the influences of different types of transducers on the hydro-generator vibration measurement, can be further studied.

Acknowledgments
Supported by the Open Research Subject of Key Lab of Hydraulic Machinery Transients, Ministry of Education of China.

References
[1] Qu Weide. Manual of mechinal vibration[M]. Beijing: China Machine Press, 1992 [in Chinese]
[2] CEI/IEC 994: 1991, Guide for field measurement of vibrations and pulsation in hydraulic machines (turbines, storage pumps and pump-turbines)[s]:59
[3] HU Huan, Xu Zhaoxi. The principle of eddy current sensor and its application on turbine supervisory instrumentation in power plant[J]. Bao steel technology. 2015(5):62-66
[4] Shi Zhensheng. Hydraulic turbine [M]. Beijing: Hydraulic and electric power press. 1992: 155
[5] Youping Li, Hanli Weng, Jian Cheng, Fei Xiang. Performance Analysis for Francis Hydraulic Turbine based on Normalized Operating Condition and its Application[J]. CHEMICAL ENGINEERING TRANSACTIONS. 2015(46): 1135-1140
[6] Qin Daqing, Zhao Hongtian, Zhaoyang. Some New Views on Francis Turbine Stability[J]. Large Electric Machine and Hydraulic Turbine. 1998(3): 43-50
[7] Zhang Xiaodong, Xie Siying, Niu Hang, Zhang Ping, Jia Binghui. Research on Dynamic Measurement Technology of Fiber Optic Sensors and Their Development[J]. Journal of Vibration, Measurement & Diagnosis. 2015, 35(3): 409-416