Application of Wavelet Analysis in the Vibration Signal of the High Dam Drainage

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Abstract. Wavelet analysis is a localized time-frequency analysis method, it uses the combination of time domain and frequency domain to show the characteristics of a signal. In this paper uses the wavelet analysis to decompose the vibration signal in different frequency band. And we can get the energy of the signal in different frequency band and the vibration characteristics of the slab by decomposing different frequencies and the different scales of the signal analysis at the different frequency band. According to the signal noise sigma, doing the wavelet threshold noise reduction uses the general threshold, the threshold set by Birge-Massart strategy, the threshold set by penalty strategy and the strategy of the threshold to estimate sample signal, then gets the best scheme.

1. Introduction
Under the interaction of high-speed flow, water-gas two-phase flow and flow-structure, the damage of discharge structure is common. Therefore, how to accurately get and analyze the effective information in the dam safety monitoring system is particularly important.

The traditional signal analysis method is Fourier transform. However, because it can not describe the local frequency characteristics of the signal, it is no longer an effective analysis method for non-stationary signals. Wavelet analysis is a new development of Fourier analysis. From the microscopic point of view, the essential difference between wavelet transform and Fourier transform is caused by the different localization properties of wavelet and sinusoidal wave. From the macroscopic point of view, Fourier analysis is a global domain analysis, while wavelet analysis is a localized time-frequency analysis. It can extract many useful information from signals, and it is a unified processing framework of various signal processing methods (such as time-frequency analysis, multi-scale analysis). Its fast algorithm brings great convenience for analyzing and solving practical problems[1].

In this paper, wavelet analysis is used to decompose vibration signals in different frequency bands, and the energy of vibration signals in different frequency bands is counted. The results show that the vibration energy of plunge pool floor is mostly concentrated in the low frequency part, and its distribution is consistent with the power spectrum calculated by AR model. According to the noise of signal, the universal threshold and the heuristic SURE threshold based on sample estimation are used to denoise the signal by using the wavelet soft threshold. By comparison, the heuristic SURE threshold filtering is the best scheme.
2. Wavelet analysis of vibration signal of plunge pool floor

This paper, the vibration displacement signal of the plunge pool floor of Ertan hydropower station is analyzed. The A21-A29 measuring points was arranged in the right corridor in turn. The A12-A18 measuring points are arranged in the left corridor. During the flood season of 2009, the vibration of bottom slab, slope and dam body of plunge pool was observed for three consecutive days. The frequency of sampling is 200 Hz. Each working condition was taking sample. The sampling data length is 60000 (The data length of first group to fifth is 36000, The data length of twentieth group is 59400). In order to ensure the reliability of the samples, repeated sampling times are required for each working condition as many times as possible. A total of 29 sets of vibration data were collected. This paper mainly analyses two typical working conditions. As shown in Table 1.

Table 1. Working table of vibration observation.

| serial number of Working condition | open pore | Opening degree | Upstream water level | Downstream water level |
|-----------------------------------|-----------|----------------|---------------------|-----------------------|
| 1                                 | 3,4# middle spillway | 41.08 | 0.93 | 51.74 |
| 2                                 | 2,3,4,5,6# surface spillway, 1# flood discharging tunnel | 28.95 | 0.94 | 67.03 |

Daubechies 4 wavelet is used to decompose the vibration signals of plunge pool floor with 8-layer wavelet. The sampling frequency of the observed signal is 200 Hz. According to the sampling theorem, the truncation frequency of Nyquist is 100 Hz, that is, the analysis frequency of the signal is 100 Hz. According to the principle of multi-resolution analysis, the signal is decomposed into two parts: low-frequency and high-frequency. The frequency band of the two parts of the signal is half of the signal band before decomposition. The original signal \( S = a_8 + d_8 + d_7 + d_6 + d_5 + d_4 + d_3 + d_2 + d_1 \).

![Wavelet decomposition of A12 signal from plunge pool floor of the first condition.](image)

Figure 1. Wavelet decomposition of A12 signal from plunge pool floor of the first condition.

Fig. 1 shows the one-dimensional discrete wavelet decomposition of the A12 measurement point signal of the one condition. The low-frequency signal represents the large-scale turbulent vortices in turbulence. They have obvious vortices structure, high regularity and repeatability. In the high frequency parts such as \( d_1 \) and \( d_2 \), the vibration amplitude is small and the frequency is high, which can be considered to be caused by noise. The detail part of the signal, i.e. the high frequency part, represents the small-scale vortices moving randomly in the flow. The time-averages are close to or equal to zero. Although the values are small, they can not be ignored. Fig. 1 shows from the details of the signals that there are beat phenomena in different degrees. The higher the frequency of the signals, the more obvious
the beat phenomena. This shows that the frequencies of the signals in the high frequency band are close to each other, and the scale of the small-scale eddies in the flow is close to each other. The low-frequency and large-amplitude components of fluctuating uplift force or fluctuating pressure is the main motive force for plate caving. And the impulse loads of high frequency and large-amplitude with short acting time play a controlling role of the destruction of water stop between plates, the separation of fragments and holes, and the loosening of anchor bars.

Tables 2 and 3 show the energy statistics in frequency domain for the decomposed signals of typical working conditions.

### Table 2. Frequency Domain Distribution of Vibration Energy at Typical Measuring Points of the first condition.

| Measurement point | Frequency        | E1 (%) | E2 (%) | E3 (%) | E4 (%) | E5 (%) | E6 (%) | E7 (%) |
|-------------------|-----------------|--------|--------|--------|--------|--------|--------|--------|
| A12               | 50–100          | 3.90%  | 2.13%  | 1.10%  | 0.95%  | 3.04%  | 15.00% | 28.98% | 29.15% |
| A15               | 6.25–12.5       | 3.90%  | 2.08%  | 1.10%  | 1.06%  | 3.84%  | 19.54% | 30.13% | 26.25% |
| A18               | 3.125–6.25      | 1.06%  | 0.59%  | 0.37%  | 0.73%  | 3.79%  | 19.70% | 34.77% | 26.55% |
| A21               | 1.5625–3.125    | 4.79%  | 2.61%  | 1.34%  | 1.01%  | 2.98%  | 14.95% | 29.04% | 26.75% |
| A24               | 0.78125–1.525   | 4.45%  | 2.43%  | 1.22%  | 1.13%  | 3.50%  | 18.13% | 31.14% | 25.19% |
| A27               | 0.390625–0.78125| 2.43%  | 1.28%  | 0.72%  | 0.92%  | 4.59%  | 20.64% | 32.30% | 24.42% |
| A29               | 0.00–0.390625   | 1.42%  | 0.76%  | 0.45%  | 1.12%  | 6.46%  | 23.19% | 34.69% | 21.84% |

From the table, it can be seen that for working condition 1, the frequency band with the largest energy is d3, which ranges from 0.78125 Hz to 1.5625 Hz. The energy proportion of the measured points on the bottom of the plunge pool is 28.98%–34.77%. The energy occupied varies according to the location of the plunge pool, which is related to the landing point of the tongue. The frequency range is 0.390625–0.78125 Hz, and the energy proportion of the plunge pool floor is between 21.84% and 29.15%. AR model is used to estimate the power spectrum of working conditions 1 and 2 at A18. The results are shown in figs. 2 and 3.
3. Noise Reduction Processing of Vibration Signal

Because of the obvious low frequency and small amplitude characteristics of vibration signals of plunge pool floor flood discharge, it is easy to be disturbed by noise. The signal-to-noise ratio and signal reliability will be reduced to varying degrees after the noise signal is mixed in. So how to suppress noise interference in vibration signal becomes a key problem to improve signal accuracy. In practical engineering applications, the analyzed signal may contain many peaks or abrupt parts. Compared with traditional methods, wavelet transform has the characteristics of time-frequency localization and multi-resolution, so it can well preserve the abrupt parts of the signal while removing noise.

3.1. Basic Principle of Wavelet Denoising

Signals and noises have different behavior in the wavelet domain, and their wavelet coefficients have different trends with the scale. With the increase of scale, the amplitude of noise coefficient decreases rapidly to zero, while the amplitude of real signal coefficients is basically unchanged. The essence of processing is to reduce or even completely eliminate the coefficients generated by noise, while retaining the coefficients of real signal to the maximum extent. Finally, the original signal is reconstructed from the processed wavelet coefficients, and the optimal estimation of real signal is obtained. [2]

3.2. Wavelet filtering of vibration signal of plunge pool floor

The process of wavelet filtering is generally completed in three steps: 1) wavelet transform; 2) non-linear processing of wavelet coefficients to filter noise; 3) inverse wavelet transform. The core of wavelet filtering is to modify the wavelet coefficients according to certain criteria in the second step so as to reduce or remove noise without losing too much signal. The existing methods can be divided into Bayesian method and non-Bayesian method. Among them, non-Bayesian method can be roughly divided into three kinds: spatial correlation filtering, modulus maximum reconstruction filtering, and wavelet threshold filtering. This paper chooses the soft threshold filtering method in the wavelet domain. It is not only simple to implement, but also has a small amount of calculation and good filtering effect. When using threshold filtering in wavelet domain, the selection of threshold value is very important. Different threshold values have direct influence on the filtering effect. In this paper, Symlets 4 wavelet
is used to decompose the signal into four layers, and the universal threshold, threshold of Birge-Massart strategy, penalty strategy, sample estimation are used to reduce the noise of Ertan vibration signal by wavelet threshold. The results are shown in Table 4 and Table 5.

Table 4. Main parameters of A15 measuring point after noise reduction with different thresholds of the first condition.

| Noise reduction method                  | Energy ratio | Standard deviation |
|----------------------------------------|--------------|--------------------|
| Penalty threshold noise reduction      | 0.958215601  | 79.5802155         |
| Birge-Massart noise reduction          | 0.9590611    | 76.3772183         |
| General threshold noise reduction      | 0.958203285  | 79.6620154         |
| Heuristic SURE Threshold noise reduction| 0.960246121  | 75.6700573         |

Table 5. Main parameters of A15 measuring point after noise reduction with different thresholds of the second condition.

| Noise reduction method                  | Energy ratio | Standard deviation |
|----------------------------------------|--------------|--------------------|
| Penalty threshold noise reduction      | 0.999245182  | 86.4121045         |
| Birge-Massart noise reduction          | 0.999225266  | 88.1673581         |
| General threshold noise reduction      | 0.999176328  | 96.0570931         |
| Heuristic SURE Threshold noise reduction| 0.999479524  | 75.4587948         |

By comparing the data in tables 4 and 5, it can be seen that the effect of heuristic SURE threshold noise reduction is better than that of other three thresholds. Higher energy ratio shows that the noise reduction does not abandon too many components of the signal. While ensuring smoothness, the useful information of the signal is well preserved. Lower standard deviation indicates that the noise reduction signal has a good similarity with the original signal ratio. The A15 measuring point shows strong low frequency characteristics under the No. 1 working condition (opening the No. 3 and No. 4 middle holes). Because of the weak vibration caused by flood discharge and the serious noise interference, the energy reduction after filtering is large, and the filtering effect is obvious. The energy change before and after filtering is not obvious when No. 2, 3, 4, 5 and 6 meter holes are opened, which is due to the strong vibration caused by flood discharge and the weak influence of noise. Fig. 4 is the reconstructed image of the A15 measuring point in working condition 1 after soft threshold filtering with different thresholds.

Figure 4. Reconstructed Graph after Threshold Filtering at A15 Measuring Point of the first condition.
4. Conclusion
(1) The measured vibration signals are decomposed by 8-layer wavelet transform. The results show that the vibration energy of the bottom plate of the plunge pool is mostly concentrated in the low frequency part, and its distribution law is consistent with the power spectrum calculated by AR model. Compared with different working conditions, the more violent the plate vibration is, the more obvious the low frequency characteristics are, and the more concentrated the energy is.
(2) Wavelet filtering can effectively remove the noise components of vibration signals of plunge pool floor, while retaining the details of the original signal to the maximum extent, and can reflect the essential characteristics of the original signal to the maximum extent.
(3) Compared with other thresholds, the model based on heuristic SURE thresholds has better filtering effect, which provides a reliable guarantee for further analysis of vibration signals of plunge pools and accurate results.

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