# Pressure fluctuation analysis and extreme pressure prediction in the transient processes of pumped storage power station

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**Abstract.** The analysis of hydraulic transient process is very important for the design and operation of pumped storage power (PSP) station. The one-dimensional mathematical model is often used in the transient process calculation, by which the maximum value at the spiral case inlet and minimum value at the draft tube inlet can be obtained. However, the one-dimensional mathematical model only provides cross section pressure trends at spiral case inlet and draft tube inlet, and the pressure fluctuation in load rejection cannot be revealed. But the pressure fluctuation amplitude of pump turbine in load rejection process is proved to be huge by test on site. In load rejection test, the measured pressure signals obtained from one or two taps, and the measured pressures affected by tap locations, and polluted by noise. So there exists great difference between the measured extreme values and numerical extreme values. To improve the accuracy of theoretical prediction, analysing the measured data and extracting the pressure fluctuation required in computed results are needed. This paper analyses the load rejection test results in generating mode and pumping mode of a PSP plant using empirical mode decomposition (EMD) method. The measured results at spiral case inlet and draft tube inlet are successfully separated to the trend terms and pulsation terms. Comparison between the measured trends and theoretical calculated results are also performed. The pressure fluctuation value superposed in the transition process calculated result of extreme pressure is recommended, which is of great significance for the safe operation of the PSP station.

## 1. Introduction

The amplitude of pressure fluctuation of pump turbine is much larger than that of conventional turbine, due to the effects of rotor stator interference (RSI), rotational stall, vortex and other factors [1] [2], especially in load rejection process, the pressure fluctuation amplitude may be up to 100 meters [3]. However, there are few studies on pressure fluctuation in transient process. During the engineering design, the pressure trends of the spiral case inlet section and draft tube inlet section can be calculated by the one-dimensional mathematical method [4]. Based on the calculated results, the extreme pressure of the PSP station in transient process can be forecasted by adding a certain proportion pressure fluctuation and calculated deviation from empirical value. The values of pressure fluctuation and calculated deviation are generally selected according to the following principles: for PSP station with maximum head over 200m, the 5% to 7% of net head before load rejection is usually given as the pressure fluctuation value at spiral case inlet, the calculated deviation of the 10% increase pressure can be selected ; the pressure fluctuation value at draft tube inlet is usually given 2% to 3.5% of net head before load rejection and the calculated deviation can be selected 7% to 10% of pressure drop. However, the measured value in load rejection is much larger than the above-mentioned experience value, because

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the acquired data is influenced by the measurement method, the measuring point location, the length of measuring pipeline and the dynamic response characteristic of the sensor, etc. Hence, in this paper we analysed the test results of load rejection of a pump-turbine at a case power plant using empirical mode decompositon (EMD) method, the measured pressures were successfully separated into the trend terms and pulsation terms. The peak to peak (p-p) values of the pressure pulsation were obtained by analysing the pulsation terms with 95% confidence interval method, and the calculated deviations were obtained by comparing the trend terms with the numerical simulation results.

## 2. Analysis method of the measured data and pressure fluctuation

### *2.1. EMD method*

The EMD method is an adaptive decomposition method proposed by N.E. Huang et al., Which can be used for decomposing nonlinear and non-stationary signals into a series of frequency modulation and amplitude modulation signals. The signals are decomposed into a series of Intrinsic Mode Function (IMF) with EMD. An IMF is a function that satisfies two conditions: (1) The number of extreme and the number of zero crossings in the whole data set must either equal or differ at most by one; (2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero [5].

A signal x(t) can be decomposed with EMD as follows [6]:

Calculating all the extreme points of the signal x(t).

Interpolating all the maxima with a cubic spline function obtain the upper envelope, which is defined as u(t), then repeat the procedure for all the minima to produce the lower envelope, which is defined asl (t).

The mean value of u(t) and l(t) is designated as $m_1(t)$, that is

$$m_1(t) = \frac{u(t) + l(t)}{2} \tag{2.1}$$

The difference between the x(t) and $m_1(t)$ is the first component $h_1(t)$; that is

$$h_1(t) = x(t) - m_1(t) \tag{2.2}$$

IF $h_1(t)$ is not an IMF, we can repeat the above procedure for k times, until $h_k(t)$ is an IMF, then it is designated as $c_1(t)$ , that is

$$c_1(t) = h_k(t) = h_{k-1}(t) - m_k(t) \tag{2.3}$$

In which,$c_1(t)$ is the first IMF component from the data.

The sifting process can be stopped by the following criteria[5]:

$$SD = \sum_{t=0}^{T} \frac{\left|h_{k-1}(t) - h_k(t)\right|^2}{h_{k-1}^2(t)} \le 0.2 \tag{2.4}$$

The above steps are also called the sifting process of the intrinsic mode function .The first IMF component $c_1(t)$ can be obtained by the above process.

The $c_1(t)$ can be separated from the rest of the data by equation (2.5)

$$r_1(t) = x(t) - c_1(t) \tag{2.5}$$

The residue $r_1(t)$ is treated as the new data and subjected to the same sifting process as described above. This procedure can be repeated on all the subsequent $r_j(t)$, and the result is

$$r_2(t) = r_1(t) - c_2(t), \ldots\ldots, \quad r_n(t) = r_{n-1}(t) - c_n(t) \tag{2.6}$$

By summing up the equations (2.5) and (2.6), equation (2.7) can be obtained.

$$x(t) = \sum_{i=1}^{N} c_i(t) + r_N(t) \tag{2.7}$$

In which , $c_i$(t) is the i-th order IMF. According to the literature [7], the lower order IMF represents the higher frequency component, and the higher order IMF represents the lower frequency component, that is, the signal frequency component represented by the IMF decreases gradually as the order increases. The residual signal of a signal trend can also be treated as a higher order IMF.

By summing up higher order IMF and the residue, we can obtain the trend terms of pressure $T$(t), that is

$$T(t) = \sum_{i=n}^{N} c_i(t) + r_N(t) \tag{2.8}$$

By summing up the first n-1 signals, we can obtain the high frequency component of the pressure signals， and it is the difference between the original signals and the trend terms， which is defined as a fluctuation term, that is

$$P(t) = \sum_{i=1}^{n-1} c_i(t) = x(t) - T(t) \tag{2.9}$$

*2.2. Analysis method of the pressure fluctuation*

The fluctuation terms are analysed with 95% confidence interval, which is the statistical concept, and it is described as follows: Estimating the overall average by means of the interval estimation, we must have three elements, which are the point estimator and the sample mean $\bar{x}$ , and the average sampling limit deviation Δx, and the confidence degree F (t). The equation is

$$\mathrm{P}(\bar{x} - \Delta\mathrm{x} \le \bar{X} \le \bar{x} + \Delta\mathrm{x}) = \mathrm{F(t)} = 1 - \alpha \tag{2.10}$$

In which $\Delta\mathrm{x} = \mathrm{t}\sigma$ , and the t is the probability and the σ is mean square deviation of the sample, that is

$$\sigma = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_3 - \bar{x})^2 + \cdots + (x_n - \bar{x})^2)}{n}} \tag{2.11}$$

When F(t) is 0.95, the t is 1.96 according to the normal distribution probability table.

The process of analysing the pressure fluctuation is as follows:

If the sampling frequency of the measured pressure is n ， we treat 1 second as a statistical interval, then we can obtain the mean pressure fluctuation by moving average method according to equation (2.12) as follows:

$$\overline{P_k} = \frac{P_{k-n/2} + P_{k-n/2+1} + P_{k-n/2+2} + \cdots + P_{k+n/2}}{n} \tag{2.12}$$

In which $P_k$ is the fluctuation pressure at the time k point.

Instead $\overline{x}$ and $x$ in equation (2.12) with $\overline{P_k}$ and p, we can obtain the mean square deviation of the of pressure pulsation $\sigma_p$,that is

$$\sigma_p = \sqrt{\frac{(P_1 - \overline{P_k})^2 + (P_2 - \overline{P_k})^2 + (P_3 - \overline{P_k})^2 + \cdots + (P_n - \overline{P_k})^2)}{n}} \quad (2.13)$$

When the confidence interval is 95%, we can obtain the confidence interval of the pressure pulsations according to equation (2.10), then connect all the maxima in the confidence interval as the upper envelope and connect all the minima in the confidence interval as the lower envelope.

If the fluctuation value at time k is greater than the point in the upper envelope, then make its value equal to the point in the upper envelope; If the fluctuation value at time k is less than the point in the lower envelope, then make its value equal to the point in the lower envelope.

Then we can obtain the peak-to-peak value of pressure fluctuation with specified confidence interval.

### *2.3. Decomposition of the measured pressures*

Taking a PSP station as an example, the measured pressures at the spiral case inlet and at the draft tube inlet in load rejection were analysed.

The measured pressures at spiral case inlet were decomposed into the trend terms and pulsation terms by EMD method. Comparison between the measured trend terms and the numerical calculated results was also performed, which is illustrated in figure 1.

Fluctuation terms were analysed with 95% confidence, then the peak-to-peak amplitude of fluctuation in the confidence interval was obtained, which is illustrated in figure 2.

By summing up the pressure fluctuations in the confidence interval and the trend terms, the pressures in the confidence interval were obtained, which is illustrated in figure 3.

The measured pressures at the draft tube inlet in load rejection were analysed as the same process, which are illustrated in figure 4 to figure 6.

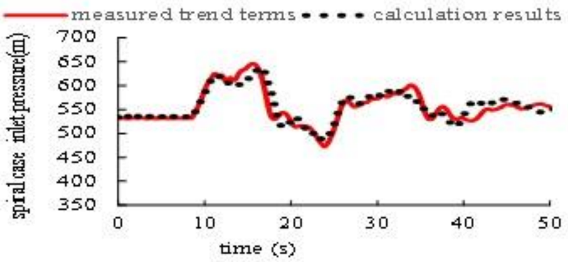


**Figure 1.** Comparison between Calculated results and measured trend terms of spiral case inlet pressures

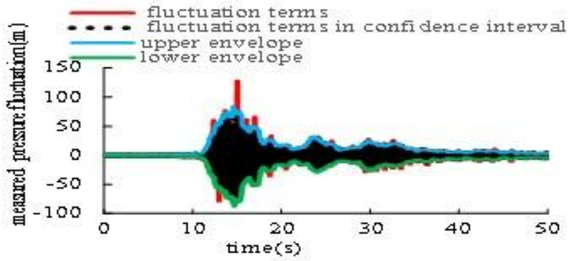


**Figure 2.** Analysis results of spiral case inlet pressure fluctuations

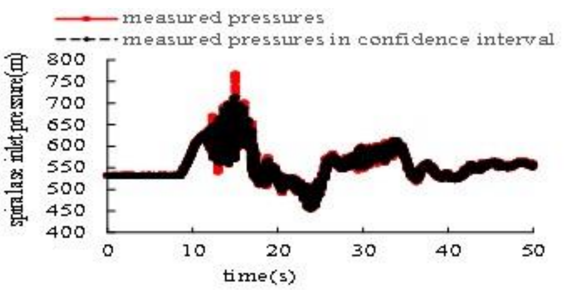


**Figure 3.** Comparison between raw measured pressures and pressures in confidence interval at spiral case inlet

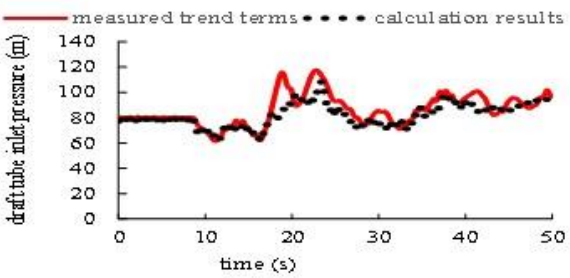


**Figure 4.** Comparison between Calculated results and measured trend terms of pressure at draft tube inlet

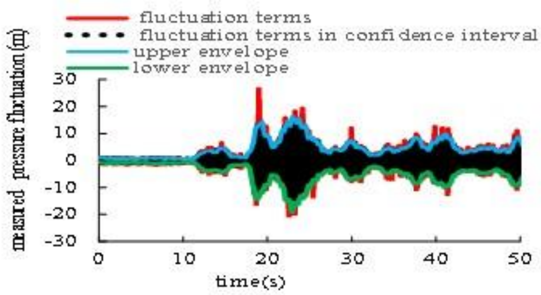


**Figure 5.** Analysis results of draft tube inlet pressure fluctuations

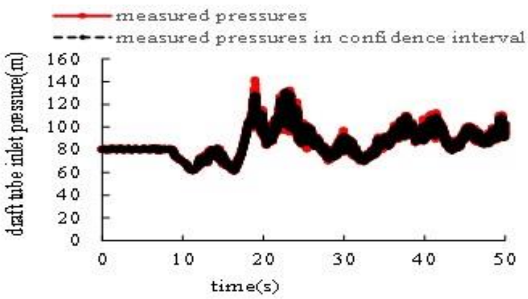


**Figure 6.** Comparison between raw measured pressures and pressures in confidence interval at draft tube inlet

## 3. Results analysis of a PSP power station

In this section, the measured pressures at spiral case inlet and draft tube inlet of a PSP station were decomposed into trend terms and fluctuation terms with EMD method, the numerical simulation model of this station were established with LTS-SJD-Model , which is a professional software used for calculation of hydraulic-mechanical transient process in hydropower station. The Calculated deviations were obtained by comparing the trend terms and calculations, and the peak-to-peak values of fluctuation pressures in transient process were obtained by analysing the fluctuation terms with 95% confidence. The extreme pressures in transient process of this station were predicted.

### *3.1. Basic parameters and numerical simulation model of the PSP station*

The numerical simulation model of a PSP station is shown in figure 7, the basic parameters of this station is shown in table 1.

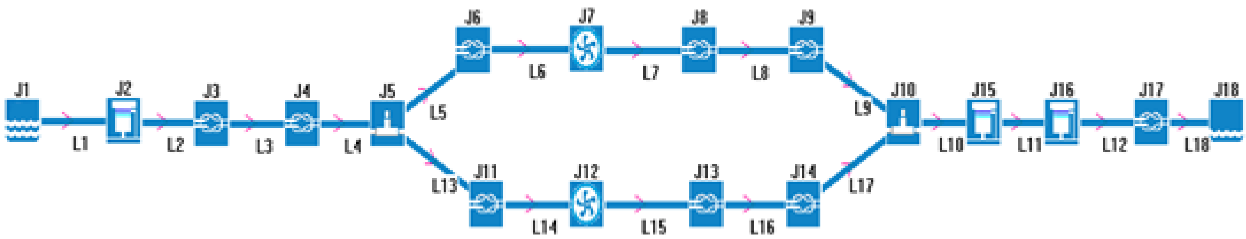


**Figure 7.** Numerical simulation model

**Table 1.** Basic parameters of the PSP station

| Unit number | Rated capacity (MW) | Rated speed (r/min) | Installation elevation (m) | Runner diameter (m) | Rated discharge ($m^3/s$) | Rated head (m) | Max. gross head (m) | Min. gross head(m) |
|---|---|---|---|---|---|---|---|---|
| 4 | 375 | 375 | 107.0 | 4.86 | 96.6 | 447 | 502.9 | 420.96 |

### 3.2. *Calculated* cases

The cases listed in table 2 and table 3 were performed by numerical simulation, which are the same as the tested cases of load rejection.

**Table 2.** Calculated cases in turbine mode

| Case | One unit rejects 100% load | Two units reject 100% load |
|---|---|---|

| Unit | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
|---|---|---|---|---|---|---|---|---|
| Head water level (m) | 660.60 | 663.35 | 659.93 | 667.13 | 662.6 | 662.6 | 660.60 | 660.60 |
| Tail water level (m) | 199.90 | 202.70 | 193.30 | 199.40 | 194.80 | 194.80 | 200.60 | 200.60 |
| Net head (m) | 455.79 | 455.64 | 461.68 | 462.82 | 457.20 | 457.24 | 448.89 | 448.88 |

**Table 3.** Calculated cases in pump mode

| Case | One unit rejects 100% load | | | | Two units reject 100% load | | | |
|---|---|---|---|---|---|---|---|---|
| Unit | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
| Head water level (m) | 635.80 | 666.70 | 658.00 | 666.40 | 661.10 | 661.10 | 665.70 | 665.70 |
| Tail water level (m) | 199.70 | 197.80 | 204.80 | 199.40 | 194.40 | 194.40 | 200.20 | 200.20 |
| Net head (m) | 440.00 | 471.82 | 456.48 | 469.98 | 478.01 | 478.05 | 472.17 | 472.20 |

*3.3. Analysis results*

The calculated extreme pressures and the tested trend terms are listed in table 4 and table 5 and the peak-to-peak (p-p) values of the pressure fluctuation are listed in table 6 and table 7. In table 4 and table 5, the difference is equal to the extreme pressures of the test value of the trend term minus the calculated value, which is also called calculated deviation. The percent in table 4 to table 7 is relative to the net head before load rejection. The calculated deviations at the spiral case inlet and the draft tube inlet in turbine mode and pump mode are illustrated in figure 10 to figure 13, the peak-to-peak (p-p)values of the pressure fluctuations at the spiral case and the draft tube in turbine mode and pump mode are illustrated in figure 14 to figure 17.

**Table 4.** Calculated deviations in turbine mode

| Case | | One unit rejects 100% load | | | | Two units reject 100% load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Unit | | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
| **Initial pressure at spiral case inlet** | Calculation(m) | 535.89 | 535.08 | 535.34 | 542.75 | 524.41 | 524.61 | 519.93 | 521.05 |
| | Trend term (m) | 531.42 | 528.6 | 531.44 | 536.54 | 540.06 | 523.61 | 525.32 | 523.74 |
| | Difference (%) | -0.98 | -1.42 | -0.84 | -1.34 | 3.42 | -0.22 | 1.20 | 0.60 |
| **Max. pressure at spiral case inlet** | Calculation(m) | 636.13 | 645.17 | 635.93 | 641.86 | 666.86 | 665.05 | 670.35 | 670.51 |
| | Trend term (m) | 646.01 | 656.52 | 646.73 | 653.68 | 690.23 | 676.23 | 703.19 | 719.49 |
| | Difference (%) | 2.17 | 2.49 | 2.34 | 2.55 | 5.11 | 2.45 | 7.32 | 10.91 |
| **Min. pessure at spiral case inlet** | Calculation(m) | 487.50 | 490.21 | 489.57 | 496.84 | 493.33 | 492.35 | 488.95 | 486.89 |
| | Trend term (m) | 474.06 | 481.19 | 476.23 | 479.44 | 483.28 | 463.69 | 479.04 | 468.56 |
| | Difference (%) | -1.98 | -1.98 | -2.89 | -3.76 | -2.20 | -6.27 | -2.21 | -4.09 |
| **Initial pressure at draft tube inlet** | Calculation(m) | 79.9 | 80.51 | 74.67 | 80.80 | 76.08 | 76.63 | 81.86 | 82.55 |
| | Trend term (m) | 80.32 | 81.16 | 73.06 | 76.60 | 76.14 | 74.71 | 81.33 | 81.17 |
| | Difference (%) | -0.09 | 0.14 | -0.35 | -0.91 | 0.01 | -0.42 | -0.12 | -0.31 |
| **Max. pressure at draft tube inlet** | Calculation(m) | 108.64 | 104.87 | 102.22 | 106.79 | 101.48 | 101.63 | 106.75 | 106.63 |
| | Trend term (m) | 117.77 | 103.52 | 102.51 | 108.15 | 104.90 | 105.75 | 106.98 | 110.29 |
| | Difference (%) | 2.01 | -0.30 | 0.06 | 0.29 | 0.75 | 0.90 | 0.05 | 0.82 |

| Case | | One unit rejects 100% load | | | | Two units reject 100% load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Unit | | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
| **Min. pressure at draft tube inlet** | Calculation(m) | 61.84 | 60.11 | 56.65 | 63.46 | 56.78 | 52.42 | 54.43 | 486.89 |
| | Trend term (m) | 61.60 | 56.25 | 53.22 | 61.25 | 50.55 | 50.90 | 51.58 | 468.56 |
| | Difference (%) | -0.05 | -0.85 | -0.74 | -0.48 | -1.36 | -0.33 | -0.63 | -4.09 |

**Table 5.** Calculated deviations in pump mode

| Case | | One unit rejects 100% load | | | | Two units reject 100% load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Unit | | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
| **Initial pressure at spiral case inlet** | Calculation(m) | 521.02 | 553.45 | 543.76 | 553.26 | 546.41 | 546.33 | 544.53 | 545.32 |
| | Trend term (m) | 519.46 | 545.19 | 540.82 | 549.29 | 551.19 | 547.94 | 547.29 | 543.91 |
| | Difference (%) | -0.35 | -1.75 | -0.64 | -0.84 | 1.00 | -0.71 | 0.59 | -0.30 |
| **Max. pressure at spiral case inlet** | Calculation(m) | 565.31 | 586.88 | 578.33 | 589.41 | 610.86 | 610.53 | 607.61 | 609.21 |
| | Trend term (m) | 580.64 | 586.88 | 594.68 | 596.37 | 617.62 | 616.53 | 609.67 | 604.02 |
| | Difference (%) | 3.48 | 0.00 | 3.58 | 1.48 | 1.41 | 1.26 | 0.44 | -1.10 |
| **Min. pessure at spiral case inlet** | Calculation(m) | 412.96 | 435.98 | 426.09 | 431.99 | 402.80 | 404.27 | 409.24 | 412.64 |
| | Trend term (m) | 404.97 | 428.35 | 423.72 | 432.61 | 402.61 | 396.68 | 403.64 | 409.49 |
| | Difference (%) | -1.81 | -1.62 | -0.52 | 0.13 | -0.04 | -1.59 | -1.19 | -0.67 |
| **Initial pressure at draft tube inlet** | Calculation(m) | 81.19 | 81.82 | 87.06 | 83.39 | 75.54 | 75.94 | 79.93 | 79.97 |
| | Trend term (m) | 78.91 | 78.67 | 85.57 | 82.88 | 77.32 | 76.42 | 81.69 | 82.61 |
| | Difference (%) | -0.52 | -0.67 | -0.33 | -0.11 | 0.37 | 0.10 | 0.37 | 0.56 |
| **Max. pressure at draft tube inlet** | Calculation(m) | 132.37 | 127.35 | 133.83 | 130.90 | 133.85 | 133.92 | 139.70 | 133.45 |
| | Trend term (m) | 143.05 | 129.82 | 144.01 | 140.98 | 144.71 | 140.65 | 150.16 | 129.65 |
| | Difference (%) | 2.43 | 0.52 | 2.23 | 2.14 | 2.27 | 1.41 | 2.22 | -0.80 |
| **Min. pressure at draft tube inlet** | Calculation(m) | 78.54 | 79.78 | 85.00 | 81.02 | 73.14 | 73.19 | 78.00 | 78.28 |
| | Trend term (m) | 78.35 | 76.43 | 85.12 | 82.35 | 76.25 | 76.09 | 79.21 | 81.85 |
| | Difference (%) | -0.04 | -0.71 | 0.03 | 0.28 | 0.65 | 0.61 | 0.26 | 0.76 |

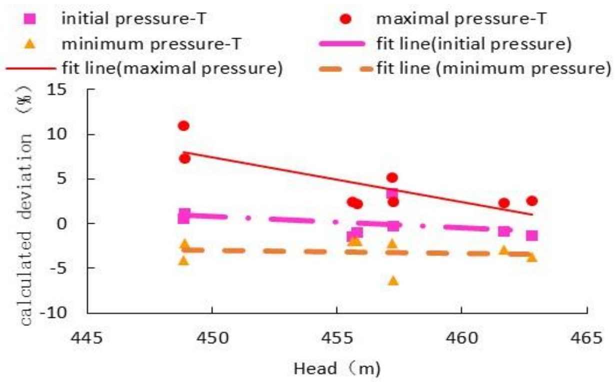


**Figure 8.** Spiral case calculated deviations in turbine mode

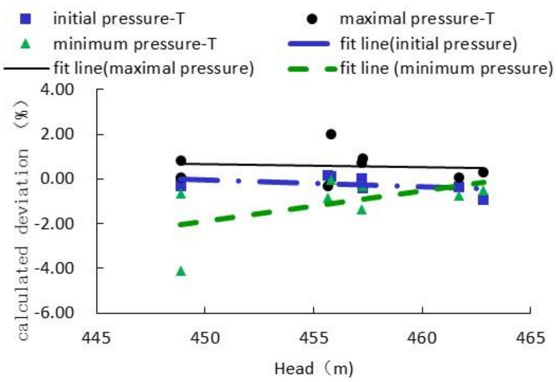


**Figure 9.** Draft tube calculated deviations in turbine mode

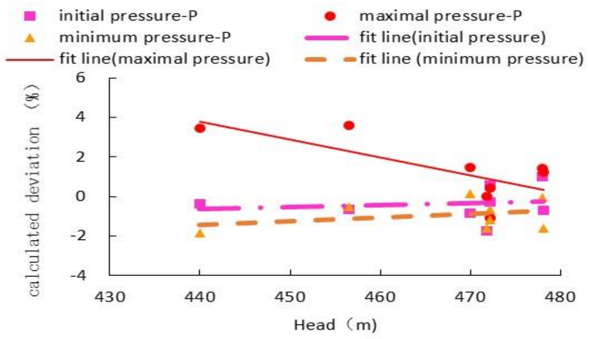


**Figure 10.** Spiral case calculated deviations errors in pump mode

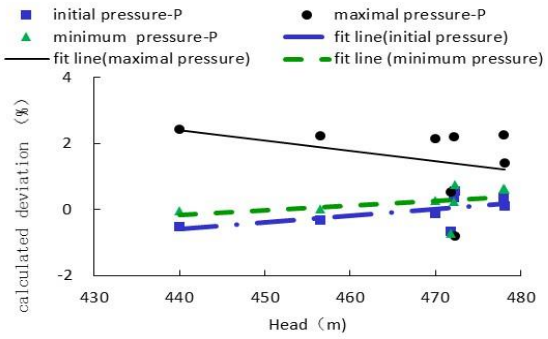


**Figure 11.** Draft tube calculated deviations in pump mode

From table 4 to table 5 and figure 9 to figure11, it can be seen that the calculated deviations in pump mode are smaller than that of turbine mode, the calculated deviations of spiral case vary from -6.27% to 10.91% in turbine mode and from -1.81% to 3.58% in pump mode, and the calculated deviations of draft tube vary from -4.09% to 2.01% in turbine mode and from -0.71% to 2.43% in pump mode .The initial calculated deviations in draft tube are less than 1% and the initial calculated deviations in spiral case are less than 2% except that the case U2 rejects load in turbine mode.

**Table 6.** Pressure fluctuations in turbine mode

| Case | | One unit rejects 100% load | | | | Two units reject 100% load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Unit | | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
| **Spiral case inlet** | Maximal(m) | 76.13 | 50.64 | 32.34 | 81.15 | 34.80 | 47.23 | 25.69 | 95.35 |
| | Minimum(m) | -73.76 | -49.72 | -33.25 | -89.49 | -36.40 | -47.38 | -26.84 | -105.8 |
| | P-P value(%) | 32.85 | 22.02 | 14.21 | 36.87 | 15.57 | 20.69 | 11.7 | 44.82 |
| **Draft tube inlet** | Maximal(m) | 15.03 | 18.72 | 1.80 | 0.22 | 12.29 | 0.87 | 12.23 | 11.09 |
| | Minimum(m) | -16.02 | -17.11 | -1.85 | -0.19 | -14.40 | -0.83 | -12.42 | -11.03 |
| | P-P value(%) | 6.81 | 7.87 | 0.79 | 0.09 | 5.84 | 0.37 | 5.49 | 4.93 |

**Table 7.** Pressure fluctuations in pump mode

| Case | | One unit rejects 100% load | | | | Two units reject 100% load | | | |
|---|---|---|---|---|---|---|---|---|---|
| Unit | | U1 | U2 | U3 | U4 | U1 | U2 | U3 | U4 |
| **Spiral case inlet** | Maximal(m) | 24.29 | 28.22 | 7.43 | 24.52 | 12.57 | 23.37 | 3.82 | 33.27 |
| | Minimum(m) | -23.79 | -28.23 | -7.47 | -21.82 | -13.66 | -24.20 | -3.81 | -33.50 |
| | P-P value(%) | 10.93 | 11.97 | 3.26 | 9.82 | 5.49 | 9.95 | 1.62 | 14.14 |
| **Draft tube inlet** | Maximal(m) | 5.21 | 13.18 | 4.36 | 0.41 | 13.48 | 1.48 | 5.59 | 3.56 |
| | Minimum(m) | -5.19 | -13.56 | -5.90 | -0.42 | -14.60 | -2.03 | -6.27 | -3.90 |
| | P-P value(%) | 2.36 | 5.67 | 2.25 | 0.18 | 5.87 | 0.74 | 2.51 | 1.58 |

IOP Conf. Series: Earth and Environmental Science **163** (2018) 012097 doi:10.1088/1755-1315/163/1/012097

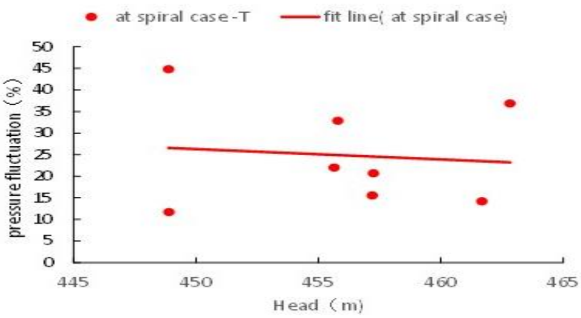


**Figure 12.** Spiral case p-p values in turbine mode

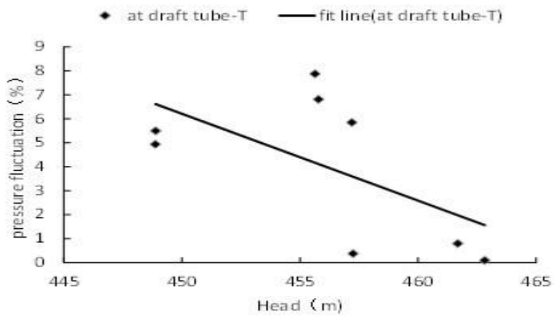


**Figure 13.** Draft tube p-p values in turbine mode

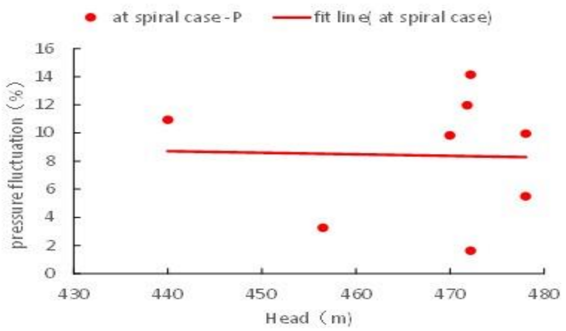


**Figure 14.** Spiral case p-p values in pump mode

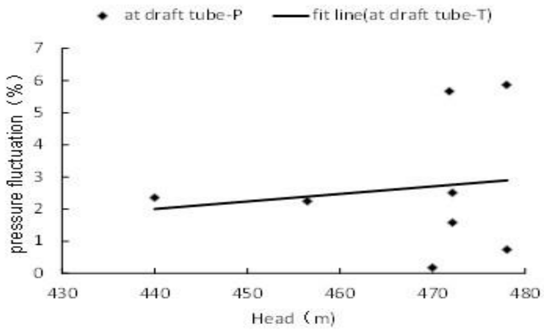


**Figure 15.** Draft tube p-p values in pump mode

From table 6 to table 7 and figure 12 to figure 15 we can find that p-p values of pressure fluctuation in pump mode are smaller than that of turbine mode. The p-p values of pressure fluctuation at draft tube vary from 0.09% to7.87% in turbine mode and from 0.18% to 5.87% in pump mode, and the p-p values of pressure fluctuation at spiral case vary from 1.62% to 14.14% in pump mode and from14.21% to 36.87% in turbine mode except the case U3 and U4 rejecting 100 % load simultaneously.

It should be noted that in the same condition pressure fluctuation of U4 is larger than U3. The reason to this phenomenon is that U4 water in the measuring pipeline resonates with the pipeline itself, which results in larger pressure fluctuation.

Therefore, it is appropriate to choose the mean value of the pressure fluctuations and calculated deviations of each unit as correction value by analysing the measured pressures comprehensively. As for this PSP station, it is suggested to choose the correction values of pressure fluctuation and calculated deviation as the table 8.

**Table 8.** Recommended values of pressure fluctuation and calculated deviation

| | In turbine mode | | In pump mode | |
|---|---|---|---|---|
| | Spiral case inlet | Draft tube inlet | Spiral case inlet | Draft tube inlet |
| Pressure fluctuation（%） | 12 | 3 | 6 | 1.5 |
| Calculated deviation（%） | 3 | 1 | 3 | 1 |

### 3.4. *Extreme Pressure Prediction*

As shown in table 9, the numerical simulation of 3 cases was performed and the calculated results and predictive results are listed in table 10, in which the predictive value is equal to the calculated value plus or minus the correction value according to the table 8. The predictive pressure at spiral case inlet is 752.34m, which is less than the designed pressure 784m, and the predictive pressure in draft tube inlet is -2.33m, which is more than the -8m. Therefore, the safety in this station can be guaranteed in transient process.

**Table 9.** Calculated cases

| Case | Head water level(m) | Tail water level(m) | Unit | Net head ( m) | Power （MW） | Description |
|---|---|---|---|---|---|---|
| 1 | 675.00 | 178.00 | U1 | 487.29 | 382.7 | Two units reject 100% load |
| | | | U2 | 487.23 | 382.7 | |
| 2 | 672.5 | 213.87 | U1 | 447.58 | 382.7 | Two units reject 100% load |
| | | | U2 | 447.52 | 382.7 | |
| 3 | 675.00 | 178.00 | U1 | 487.28 | 382.7 | U1 rejects load firstly, U2 rejects load after several seconds |
| | | | U2 | 487.23 | 382.7 | |

**Table 10.** Calculated results and predictive results

| Case | Results | Unit | Spiral case inlet pressure (m) | | Draft tube inlet pressure (m) | | Speed （%） |
|---|---|---|---|---|---|---|---|
| | | | Max. | Min. | Max. | Min. | |
| 1 | Calculated value | U1 | 669.79 | 505.25 | 84.01 | 38.69 | 130.41 |
| | | U2 | 670.22 | 504.81 | 83.94 | 38.75 | 130.45 |
| | Predictive value | U1 | 742.88 | 432.16 | 103.5 | 19.2 | 130.41 |
| | | U2 | 743.3 | 431.73 | 103.43 | 19.26 | 130.45 |
| 2 | Calculated value | U1 | 685.09 | 500.81 | 113.39 | 77.17 | 29.61 |
| | | U2 | 685.21 | 500.49 | 113.39 | 76.86 | 29.65 |
| | Predictive value | U1 | 752.23 | 433.67 | 131.29 | 59.27 | 29.61 |
| | | U2 | 752.34 | 433.36 | 131.29 | 58.96 | 29.65 |
| 3 | Calculated value | U1 | 646.04 | 513.69 | 84.6 | 34.3 | 26.82 |
| | | U2 | 651.6 | 498.06 | 84.68 | 17.16 | 31.18 |
| | Predictive value | U1 | 719.13 | 440.6 | 104.09 | 14.81 | 26.82 |
| | | U2 | 724.68 | 424.98 | 104.17 | -2.33 | 31.18 |

## 4. Conclusions

With EMD method, the measured pressures at spiral case inlet and draft tube inlet under 12 cases of turbine mode and pump mode were decomposed into the trend terms and pressure fluctuation terms. The pressure fluctuations were analysed with 95% confidence level, and the calculation deviations were given by comparing the calculation results with the trend terms. And then the extreme pressures of the PSP station were predicted based on the obtained pulsation amplitude and calculation deviation. The conclusions are as follows:

- The test results prove the existence of the large pressure fluctuations in transient process, the maximal value reaches up to 40% of the net head before load rejection.
- The pressure fluctuations in pump mode are much smaller than that in turbine mode. The amplitude is only about half of that in turbine mode.
- For the calculation results of pump turbine transient process at spiral case inlet and draft tube inlet, the recommended calculation deviation are respectively 3% and 1% of the net head before load

IOP Conf. Series: Earth and Environmental Science **163** (2018) 012097 doi:10.1088/1755-1315/163/1/012097

rejection. The recommended pressure fluctuations are different for turbine mode and pump mode, they are respectively 12% and 6% at spiral case inlet and 3% and 1.5% at draft tube inlet.

- The extreme pressures of transient processes in a PSP station were predicted with the recommended pressure pulsations and calculation deviations. The results prove the design values meet the safety requirements of the power station.

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