Experimental investigation on the unsteady pressure pulsation and vibration of a nuclear pump test loop

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Funding information
National Natural Science Foundation of China, Grant/Award Number: U1808214; China Scholarship Council, Grant/Award Number: 202006060155; The Fundamental Research Funds in Dalian University of Technology, Grant/Award Number: DUT20LAB125

Abstract
The nuclear reactor coolant pump (RCP) is the key equipment of the Pressurized Water Reactor, of which the coolant circulation inherently brings flow fluctuation and, therefore, flow-induced vibration exists, which is detrimental to the safe and stable operation of nuclear power plants. Experiments were carried out on a nuclear pump test loop to investigate the characteristics of pressure pulsation and vibration under various rotational speeds and operational temperatures. Signals of pressure pulsation and vibration synchronously measured from the sensors located among the test loop and the bottom of the motor were analyzed by the Root Mean Square and the Fast Fourier Transform methods. Pronounced pressure pulsation peaks corresponding to the blade passage frequency and its higher harmonics are captured, and pressure pulsation amplitude variations are closely associated with the sensor positions and operating conditions. Vibration magnitude along the outlet direction of the nuclear RCP is the largest and increases with the increasing rotational speed but not the operating temperature. Finally, a coherent analysis was conducted between the vibration at the bottom of the motor and the unsteady pressure pulsation in the test loop. This study can provide meaningful scientific guidance in practical engineering applications.

KEYWORDS
coherent analysis, high pressure, high temperature, nuclear pump test loop, pressure pulsation, vibration

1 | INTRODUCTION

As the heart of the nuclear power plant, the reactor coolant pump (RCP) circulates the coolant to carry away the decay heat from the reactor core.1 Coolant circulation inherently brings flow fluctuation and, therefore, flow-induced vibration exists, threatening the stable operation of nuclear power plants, especially the nuclear RCP, which is directly suspended on the cold side of the steam generator. Pressure pulsation can also give rise to acoustic system resonances and fatigue fractures of the pump components.2 Therefore, it is urgently necessary to make a comprehensive understanding of the characteristics of pressure pulsation as well as its induced vibration.
Numerical simulation is an effective research method to study the pressure pulsation characteristics in the hydraulic machinery, of which are Reynolds averaged Navier–Stokes (RANS) equations, large-eddy simulation (LES), and Detached Eddy Simulation (DES) methods. The RANS method has been widely applied with its high computational efficiency. Yun et al. investigated the pressure pulsation characteristics in a scaled model RCP with different inflows by solving the RANS equation with the $k − \varepsilon$ turbulent model, the predominant frequency components of the inlet, and outlet pressure pulsation both located at the double rotor passing frequency. Compared with the RANS, the LES can better capture the detailed vortex structure but require a higher computing resource while the DES is in between. Jiang et al. simulated the flow-induced mechanical vibrations and noise in a centrifugal pump with an LES-based CFD program and a parallel explicit dynamic finite element method code, vibration modes at blade-passing frequencies were extracted and presented. Posa and Lippolis reported the LES method coupling with an immersed boundary methodology used in a centrifugal pump, pressure pulsation sensitivity to the flowrate, and diffuser blade orientations were investigated. The Delayed Detached Eddy Simulation method was applied to investigate the unsteady flow structures and pressure pulsations of a centrifugal pump at off-design conditions and the stall frequency were captured.

Compared with the computational fluid dynamic methods, experimental measurements are the most direct ways to study pressure pulsation characteristics. Pei et al. experimentally investigated the nonlinear pressure pulsation characteristics in a Residual Heat Removal Pump. Xu et al. researched the unsteady pressure pulsation characteristics in an RCP with a steam-generator simulator, and the influence of rotational speed on pressure pulsation was investigated. The noncontact measurement techniques such as Laser Doppler Velocimetry and Particle Image Velocimetry are indispensable approaches to acquiring the unsteady flow information within a special pump. Zhang et al. obtained the velocity and vorticity distributions in the diffuser and spherical casing of an RCP model by using the PIV method, and the complexity of the flows in the RCP was revealed. Both the contact and the noncontact measurements can be further used to validate the numerical simulation.

With the development trend of high speed, high lift, and efficiency, the turbomachinery has inevitably increased the potential for fluid/structure interaction problems, particular attention must be paid to the pressure pulsation and its induced vibration, the vibration levels should be minimized. Guo and Maruta measured the pressure pulsation and its induced vibration of the impeller in a centrifugal pump, it was found that the resonance of the impeller can be excited due to the circumferential unevenness of the pressure pulsations. Gao et al. investigated the relationships between the pressure pulsation and the vibration in a centrifugal pump, signals of which were relatively similar and there was a strong correlation in frequency domain distribution, especially at the fundamental frequency. Good structural vibration characteristics are the guarantees for long-term safe, stable, and reliable operation of the nuclear RCP. However, the current research on pressure pulsation and its induced vibration by the nuclear RCP in an environment of high temperature and high pressure is still insufficient, especially the experimental investigation. To fully grasp the pressure pulsation and vibration characteristics at the high-temperature and high-pressure environments, which can provide scientific guidance in the practical engineering application.

This paper presents an experimental investigation on a nuclear pump stage to explore the characteristics of pressure pulsation and vibration in the fluid system. Dynamic pressure transducers were applied to execute transient pressure measurements of 13 monitoring points among the test loop and vibration signals measured from three sensors at the bottom of the motor. The magnitude of the pressure pulsation and vibration was evaluated via Root Mean Square (RMS) method. Special attention was paid to the pressure pulsation peaks corresponding to the blade passage frequency and its higher harmonics. Meanwhile, the influence of operating temperature and rotational speed on pressure pulsation and vibration were investigated. Finally, the correlation between pressure pulsation and vibration signals was investigated for further work to improve the safety performance of the RCP.

2 EXPERIMENTAL SYSTEM
2.1 The nuclear pump and the primary test loop

The nuclear pump employed to drive the coolant circulation in this test campaign adopts the vertical structure design, the hydraulic components are composed of a suction adapter, an impeller with four blades, a radial diffuser with seven vanes, and an annular discharge case, which are located on the canned motor, as shown in Figure 1. The nominal rotational speed of the pump $n_d$ is 1485 r/min and the other parameters such
as the nominal flow head are listed in the Nomenclature. The circulating fluid medium is water in this study.

All the experiments were conducted in a closed-loop test platform, which consisted of a nuclear pump primary loop system, an auxiliary loop system, and a control system. A general sketch of the primary test loop is shown in Figure 2, the RCP is suspended vertically on the test loop to simulate the actual operating condition. The flow rate was measured by a venture meter with an uncertainty of less than 0.5%, of which the maximum measured flow and working pressure are 15,000 m³/h and 17.3 MPa, respectively. Meanwhile, the rotational speed was measured by a nuclear grade speed sensor, based on the principle of electromagnetic induction, and the measurement accuracy of the speed was 0.2%. The temperature was measured by a platinum resistance thermometer with second-order accuracy during the experimental test.

2.2 | The auxiliary system

In the current research, we mainly focus on the pressure pulsation and vibration characteristics of the high-temperature and high-pressure environments, and the effect of temperature and speed on them. To gain these goals, the operating speed was controlled by the frequency converter. The loop system temperature and pressure are realized through the heating and cooling system and the pressure control system. Both auxiliary systems are automatically controlled. The heating method is realized by the immersion heaters controlled by Silicon Controlled Rectifier, while the cooling method is realized by loop cooling heat exchanger and flow control valve. The booster pump controls the loop pressure with the pressure relief valve. Figure 3 shows one booster pump and valve used in the pressure control system. Besides, the pump operating voltage is set at the range of 6000 + 420/−300 V.A.C. to ensure its stable operation.

2.3 | The test scheme

To obtain the pressure pulsation signal among the test loop, 13 Endevco 522M17 piezoelectric dynamic pressure transducers were mounted in the primary loop pipe. Five were in the outlet pipe section (DH1–DH5), one was on the distal branch pipe (VH6), and the other seven transducers were arranged on the upper horizontal pipe (SH7–SH13). All the pressure transducers work well at the temperature extremes of up to 538°C continuous and up to 649°C intermittents. There were also three
Wilcoxon 793 V series piezo velocity sensors (D1X, D1Y, and D1Z) located at the bottom of the motor to monitor the dynamic vibration of the RCP, as shown in Figure 2. They were installed in mutually orthogonal orientations: parallel (X-direction) and perpendicular (Y-direction) to the outlet pipe, and the axial direction is parallel to the main pump centerline (Z-direction). The resonance frequency of the vibration sensor is 15 kHz, and the working temperature range is between −50°C and 120°C. All the velocity signals were converted into displacement signals to real-time monitor the condition of the pump during the process of data acquisition. The pressure pulsation and vibration signals were connected to the B&K data acquisition system and acquired synchronously. The sampling frequency $f_s$ was set as 16 kHz and sampled for 60 s in this study.

3 | RESULTS AND DISCUSSION

3.1 | Analysis of the pressure pulsation

3.1.1 | Temperature effects on pressure pulsation characteristics

The nuclear RCP is characterized by a large flow rate, high head, working in high-temperature and high-pressure environments, and requires safe and efficient operation for about 40–60 years.29 The operating environment of the RCP changes with the work content and the physicochemical properties (density, kinematic viscosity, etc.) of coolants also change as a result. Inevitably, the dynamic characteristics of the whole system have been affected as well. Exploring this change and revealing its laws is of great significance to engineering practice.

To evaluate the pressure pulsation energy under different coolant temperatures, the RMS and Peak-to-Peak (PP) values were calculated with a 95% confidence limit to analyze the time-domain characteristics of discrete pressure signals. Meanwhile, the FFT algorithm was used to analyze the pressure spectrum characteristics. Besides, all the pressure pulsation values were converted into dimensionless form based on the PP change $\Delta H/H$, where $\Delta H = \Delta p/\rho g$, $\Delta p = p - \bar{A}$, $\bar{A}$ is the mean amplitude of the pressure, and $H$ is the head for the pump at the design condition.16

Both the maximum RMS and PP pressures measured among all the locations of the sensors in the loop, as well as the average RMS and PP pressures over the collection of sensors, present the intensity of pressure pulsation, as illustrated in Figure 4. The variation trend of the RMS and PP values with the temperature is consistent in the comparison of these four operating temperatures. The intensity of pressure fluctuation is not positively correlated with the temperature increase. As the test loop temperature increases, the RMS (or PP) value decreases first and then increases. When the thermal state (280°C) is reached, the characteristic values decrease again but are higher than that in the cold state (28°C) while the values at DH1 increase all the time. From the cold state to the thermal state, the RMS value has an increment of 31.3% at DH1, 7.6% at VH6, and 1.03% at SH13, the max, and average RMS values increase by 23.4% and 25.1%, respectively. The PP value has an increment of 29.3% at DH1, 14.3% at VH6, and 0.95% at SH13, the max, and average PP values increase by 21.3% and 27.3%, respectively. Whether it is in the cold state or the thermal state, the intensity of pressure pulsation at the outlet segment of the pump is always stronger than that at the inlet segment.
Figure 5 shows the comparison of the pressure pulsation spectrum at four temperatures under the same rotational speed. The horizontal axis $St$ represents the Strouhal number which is a nondimensional frequency. It defines the ratio between the frequency and the blade passage frequency. Some discrete peaks corresponding to blade-passing frequency ($f_{BPF}$) and its harmonic frequencies can be identified, but the dominant frequency is associated with not only the operating temperature but also the measuring position of the test loop. At the measuring point DH1, when the nuclear RCP operates in the cold state, the dominant frequency is $f_{BPF}$ and $2f_{BPF}$ is the second dominant frequency, moreover, peaks correspond to the higher harmonics of $f_{BPF}$ can be identified easily. When the operating temperature increases up to 80°C, the amplitude at $f_{BPF}$ decreases and $2f_{BPF}$ becomes the dominant frequency while $3f_{BPF}$ is the second dominant frequency. When the operating temperature is 200°C, the amplitude at $f_{BPF}$ is lower again, and other high-frequency harmonics also slightly decrease. The $3f_{BPF}$ is the dominant frequency while $2f_{BPF}$ becomes the second dominant frequency. When the thermal state is reached, the frequency component at $f_{BPF}$ could not be identified easily, the dominant frequency is $2f_{BPF}$ and the second dominant frequency is $3f_{BPF}$. Other high-frequency harmonics relatively increased slightly.

At the distal branch pipe measuring point VH6, the dominant frequency is $f_{BPF}$ and the second dominant frequency is $2f_{BPF}$ in the cold state. When the temperature is 80°C, peaks corresponding to $f_{BPF}$, $2f_{BPF}$, $3f_{BPF}$, and $7f_{BPF}$ are easily identified. What is more, the amplitude at $7f_{BPF}$ increases evidently, but the dominant frequency still is $2f_{BPF}$ and $7f_{BPF}$ is the second dominant frequency. When the temperature increases up to 200°C, the amplitude at $7f_{BPF}$ is significantly increased and becomes the dominant frequency. When in the thermal state, the amplitude at $7f_{BPF}$ is still the largest but the energy has been weakened. The frequency component at $f_{BPF}$ could not be identified easily and $2f_{BPF}$ becomes the second dominant frequency.

Just like the distal branch pipe measuring point, the dominant frequency of the inlet measuring point SH13 is $f_{BPF}$ at both 28°C and 80°C, $7f_{BPF}$ at both 200°C and 280°C. When the nuclear RCP operates in the cold state, $7f_{BPF}$ is the second dominant frequency. When the temperature increases up to 80°C, the frequency components of $f_{BPF}$ and $7f_{BPF}$ could be identified easily, of which the amplitudes have been weakened. Moreover, a low frequency of 14.5 Hz is identified. When the operating temperature is 200°C, the frequency component at $f_{BPF}$ could not be identified easily, amplitude at $7f_{BPF}$ has increased while the low-frequency component of 12.875 Hz becomes the second dominant frequency. The low frequency of 10.5 Hz becomes the second dominant frequency when in the thermal state. As the low-frequency component decreases with the temperature increasing, it can be seen as the natural frequency of the local pipeline.

What is more, to further investigate the effect of temperature on pressure pulsation, Figure 6 shows the influence of temperature on pressure pulsation amplitudes of the blade-passing frequency ($f_{BPF}$) and other main characteristic frequencies under the same speed. Not only the frequency components but also the amplitude is affected by the temperature. The amplitude of $f_{BPF}$ decreases as the temperature increases, the average reduction rate is 91% from the cold state to the thermal state. With this, just the opposite is the amplitude at $3f_{BPF}$ trends to become bigger totally when the thermal state is reached. The amplitude of $2f_{BPF}$ at DH1 increases significantly while slightly decreases at SH13, but the average amplitude of $2f_{BPF}$ at DH1 increases slightly. At 206°C, the amplitude of $7f_{BPF}$ at VH6 and SH13 is the maximum while the minimum at DH1. Furthermore, amplitudes of $f_{BPF}$, $2f_{BPF}$, and $3f_{BPF}$ at SH13 are larger than those at DH1, and pressure fluctuation at the outlet is more violent than that at the inlet.
Influence of rotational speed on pressure pulsation characteristics

During the startup of the RCP, the rotational speed gradually increased to the rated speed. Due to the pressure pulsation is excited as the impeller blades pass the diffuser blades successively. The pressure pulsation is inevitably influenced by the rotational speed, especially the intensity of pressure pulsation increases with the increase of the rotational speed. As shown in Figure 7, the nuclear RCP operates at different rotational speeds in the thermal state, the PP values as well as the RMS values significantly increased with the operational speed increasing. From 750 to 1500 r/min, the PP value has an increment of 475.4% at DH1, 230.4% at VH6, 342.2% at SH13, the RMS value has an increment of 573.5% at DH1, 287.6% at VH6, and 347.9% at SH13. The increment of the maximum and average PP value is 282.0% and 384.9%, for the RMS value is 427.8% and 428.0%, respectively. With the rotational speed increasing, the RMS and PP values at DH1 are much higher than those at SH13, it can be conducted that the pressure pulsation at the outlet is much more intense than that at the inlet.

As illustrated in Figure 8, the pressure pulsation spectrum at four rotational speeds is significantly inconsistent, the variety of rotational speeds results in the changes in the characteristic frequency which corresponds to maximum amplitude. Some discrete peaks corresponding to blade-passing frequency ($f_{BPF}$) and its harmonic frequencies can be identified, but the dominant frequency is not only associated with the rotational speed but also the measuring position of the test loop. At DH1, when the nuclear coolant pump operates at the speed of 750 r/min, $4f_{BPF}$ is the dominant frequency and the second dominant frequency is $2f_{BPF}$. When rotational speed is 900 r/min, $2f_{BPF}$ is the dominant frequency, through peak corresponding to $9f_{BPF}$ increases evidently, but the $3f_{BPF}$ is the second dominant frequency. When the rotational speed is 1200 r/min, discrete peaks corresponding to $2f_{BPF}$ and the higher harmonic frequencies of $f_{BPF}$ are significantly increased. But the dominant frequency is $2f_{BPF}$, the second dominant frequency still is $3f_{BPF}$. At the nominal rotational speed of 1500 r/min, $5f_{BPF}$ and $6f_{BPF}$ become easily identified while the dominant frequency still is $2f_{BPF}$. It can be found that the pressure fluctuation of the inlet position is mainly dominated by the $2f_{BPF}$.

At the measuring point VH6, discrete frequency components corresponding to the $f_{BPF}$ and some of its higher harmonics can be identified, but the energy has been weakened as a whole. When the rotational speed is 750 r/min, the dominant frequency is $f_{BPF}$ and $7f_{BPF}$ is the second dominant frequency. When the rotational speed is 900 r/min, $3f_{BPF}$ becomes the dominant frequency while $4f_{BPF}$ is the second dominant frequency. The rotational speed increase results in the changes in the characteristic frequency which correspond to maximum peaks. When the rotational speed increases to 1200 r/min, discrete

![Figure 5](image_url)  
**Figure 5** Pressure pulsation spectrum at three measuring points under different temperatures.
peaks corresponding to $2f_{BPF}$, $3f_{BPF}$, and $7f_{BPF}$ become evident while $f_{BPF}$ is not, and $7f_{BPF}$ is the dominant frequency. When the nuclear RCP operates at the nominal rotational speed of 1500 r/min, $7f_{BPF}$ becomes the second dominant frequency, while the amplitude at $2f_{BPF}$ increases significantly and $2f_{BPF}$ is the dominant frequency at the nominal rotational speed. The spectral analysis results show that the pressure pulsation energy becomes more concentrated in the distal branch pipe position, mainly on $2f_{BPF}$, $3f_{BPF}$, and $7f_{BPF}$.

The intensity of the pressure pulsation of the inlet measuring point SH13 decreases obviously. Some discrete peaks corresponding to $2f_{BPF}$, $3f_{BPF}$, $4f_{BPF}$, and $7f_{BPF}$ are easily identified. Moreover, one low-frequency corresponding to 10.5 Hz becomes more evident, which is independent of the rotational speed, maybe it is the natural frequency of the local pipeline. When the rotational speed is 750 r/min, the low frequency is the dominant frequency, and $4f_{BPF}$ is the second dominant frequency. With the rotational speed increasing to 900 r/min, the amplitude at the low frequency has an increment of 47.5%, but $3f_{BPF}$ becomes the dominant frequency. When the rotational speed is 1200 r/min, $7f_{BPF}$ becomes the dominant frequency and the low frequency is still the second dominant frequency with an increment of 35.6%. At the nominal rotational speed, the peak at $f_R$ becomes significant, the amplitude of which is much larger than the low frequency. The dominant and second dominant frequency is $2f_{BPF}$ and $6f_{BPF}$, respectively. The pressure pulsation at the inlet segment is influenced not only by the rotational speed but also by the low frequency.

To make a better understanding of the rotational speed effect on the pressure pulsation. Figure 9 shows the variation trend of peaks corresponding to $2f_{BPF}$, $3f_{BPF}$, $4f_{BPF}$, and $7f_{BPF}$ at four different operating speeds. It is
noted that pressure amplitudes at $2f_{BPF}$ increase rapidly with the rotational speed increases. Pressure amplitudes of VH6 and SH13 at $3f_{BPF}$ increase when the rotational speed increases to 900 r/min and then decreases until the nominal speed. But at the DH1, the pressure amplitudes of DH1 at $3f_{BPF}$ increase when the rotational speed increases to 1200 r/min, then decrease until the nominal speed. When the rotational speed is 1200 r/min, amplitudes at $4f_{BPF}$ have the minimal values, pressure amplitudes of DH1 and SH13 decrease gradually as rotational speed increases to 1200 r/min while they increase the nominal speed is reached. When it comes to the variation trend of the peaks at $7f_{BPF}$, they gradually increase as the rotating speed increases as a whole.

3.3 Analysis of the vibration at the bottom of the pump

3.3.1 Temperature effects on the vibration characteristics

During the operation of the nuclear RCP, vibration information plays a vital role which can monitor the running state of the pump in real-time. To evaluate the vibration intensity of the nuclear RCP under different coolant temperatures. The RMS and PP values with a 95% confidence limit were also applied, as shown in Figure 10. When the RCP operates at the same speed, it is easy to find that the vibration in the $X$-direction at the bottom of the motor is the highest, following the $Y$-direction, the $Z$-direction is the lowest. From the cold state to the thermal state, the vibration decreases in the $X$- and $Z$-directions while increasing in the $Y$-direction, the vibration RMS value has a decrement of 22.4% at D1X, 23.9% at D1Z while an increment of 23.6% at D1Y. Meanwhile, the vibration PP values have a decrement of 22.5% at D1X, 22.4% at D1Z, and an increment of 36.8% at D1Y. The maximum vibration amplitude always occurs at the outlet direction of the pump, which is free of the temperature effect.

To make a good understanding of the temperature effect on the vibration, the vibration spectrum at four temperatures under the same rotational speed is shown in Figure 11. At D1X, peaks corresponding to 3.5 Hz are easily captured, which is free of the temperature effect while its amplitude is not. There is a clear low characteristic frequency (2.6 Hz) that exists at the vibration spectrum, and the rotating frequency ($St = 0.25$) can be identified at D1Y. For the vibration at D1Z, the frequency amplitudes are relatively small, but the frequency components are complex. The temperature effects on the vibration amplitude corresponding to the characteristic frequency are shown in Figure 11D. It is correlated between the operating temperature and the maximum vibration frequency amplitude, but the variation trend is not obvious. At D1X, when the nuclear RCP operates in the cold state, the vibration amplitude
corresponding to the low frequency is the maximum. At D1Y, the maximum vibration amplitude occurs in the thermal condition. With the coolant temperature increasing, peaks corresponding to the low frequency gradually decrease at D1Z.

3.4 Influence of rotational speed on the vibration characteristics

During the speed increase of the nuclear RCP, the rotational speed not only affects the pressure pulsation but also the vibration. Figure 12 shows the variation of the displacement with the rotation speed increasing in the thermal state. In vibration signals at D1X, the PP (or RMS) values increase rapidly with the operating speed increasing, meanwhile, the PP (or RMS) values at D1Z increased gradually. At D1Y, the vibration increases gradually as the rotational speed increases up to 1200 r/min, but when the speed is reached the nominal speed, the PP (or RMS) values decrease but are higher than those at 750 and 900 r/min.

As illustrated in Figure 13, the vibration frequency components at four rotational speeds are significantly consistent but the amplitude is not. The same low frequency can be easily captured at D1X, which is free of the rotational speed variation. At D1Y, there is also a low frequency that can be identified, and the rotating frequency ($St = 0.25$). Some low-frequency components at D1Z can be found through the corresponding amplitudes are relatively small. Figure 13D shows the variation trend of vibration peaks corresponding to the low frequencies at four different rotational speeds. It is noted that vibration amplitudes at D1X increased rapidly with the rotational speed. And the vibration amplitudes corresponding to the characteristic frequency increase at
D1Z as well. The vibration amplitudes of D1Y increase when the rotational speed increases to 1200 r/min and then decreases until the nominal speed.

3.5 Modal test of the primary test loop

To determine the source of the low-frequency component of the vibration signal, especially the vibration at the outlet direction. One modal test was carried out via the hammering method, as shown in Figure 14, each hammer in the figure represents the direction of hammering and the response measuring point. As illustrated in the stability diagram in Figure 15, the low-frequency component corresponds to 3.6 Hz, which is the natural frequency of the whole primary test loop.

Combining the modal test results with the pressure pulsation and vibration spectrum, it can be considered that the reason for the high vibration at the outlet direction is due to the low-frequency resonance. For the current nuclear main pump in this study, the flow rate is big and the flow speed in the pipeline is high, which caused a wide-frequency excitation. Thus, there are broadband components in the low-frequency range at the pressure spectrum and high vibration peaks at the vibration spectrum, the higher speed, the larger the vibration amplitude corresponding to the low frequency,
as shown in Figure 13D. More information about the vibration can be referred to in this study.30

3.5.1 | Coherence analysis of the pressure pulsation and vibration

To investigate the relationship between the pressure pulsation among the fluid system and the vibration of the nuclear RCP, the coherence analysis was applied to build a bridge to identify the direct relationships between them. As shown in Figures 16 and 17, the coherent coefficients were calculated and compared between the maximum vibration signals (D1X) and different pressure signals in the test loop (DH1, VH6, and SH13), the solid dots indicate that the coherent coefficient values greater than 0.9. The coherence can be interpreted as a measure of the degree of linearity between the two signals versus the frequency in the normalized range between 0 and 1.31 The higher the coherent coefficient, the stronger the coherence of the two signals at the corresponding frequency.

Some discrete coherent coefficients corresponding to $f_{HPP}$ and its harmonics are greater than 0.75, which indicates that
there is a strong correlation in the frequency domain distribution of the vibration and pressure pulsation. As illustrated in Figure 16, the coherent characteristic is much more affected by the operating temperature than the measuring points of the pressure pulsation. The number of the characteristic frequency corresponding to the coherence value reached 0.9 is significantly different with the temperature increasing. Combined with Figure 18, the average coherence coefficient in the frequency band of 1–1 kHz was calculated to quantitatively evaluate the temperature effect.
Bars in the histogram show the average coherence coefficient value at three different points as well as the line chart shows the total average of the three points at different temperatures. At the same temperature, the highest branch always corresponds to the coherence coefficient between the inlet pressure pulsation and vibration while the lowest is the outlet. Indicating that the pressure fluctuation at the inlet is highly correlated with the vibration, and there is a certain convergence between them. Taken together, the coherence of the pressure pulsation and vibration gets enhanced first and then reduced with the rotational speed faster, with the highest coherence corresponding to the speed of 1200 r/min.

4 | CONCLUSIONS

Experiments were carried out on a nuclear pump test loop under the various rotational speeds and operational temperatures. The RMS, PP value, and FFT methods were applied to explore the characteristics of unsteady pressure pulsation and vibration. One modal test was conducted to determine the source of the low-frequency component of the vibration signal. What is more, a coherent analysis was concluded between the pressure pulsation among the test pipe and the vibration at the bottom of the motor.

The pressure pulsation characteristic is associated with not only the measuring positions but also the operational condition. The pressure pulsation at the outlet is much more intense than that at the inlet of the nuclear RCP. As the temperature increases, the intensity decreases first and then increases while it always increases with the increasing rotational speed. Some discrete peaks corresponding to the blade-passing frequency and its harmonics can be identified in the pressure pulsation spectrum. With the temperature heating up or the rotational speed faster, the dominant frequency varies as well as the amplitude.

The maximum vibration at the bottom of the motor occurs in the outlet direction of the nuclear RCP. The variation of the vibration displacement is more sensitive to the rotational speed than the temperature. The vibration increases rapidly with the operating speed increasing. Moreover, there is a natural frequency was determined for the reason of the high vibration in the direction of the outlet.

There is a strong correlation between the frequency domain distribution of the vibration in the outlet direction and pressure pulsation in the fluid system. The coherence is much more affected by the operational condition than the measuring position. The pressure fluctuation at the inlet is highly correlated with the vibration. With the rotational speed faster, the coherence is enhanced first and then reduced while the coherence is always enhanced as the temperature heats up.
Finally, it is expected that the present work will provide scientific guidance for practical engineering. The pressure pulsation characteristics are inevitably influenced by the various operating conditions as well as the vibrations at the bottom of the motor. What is more, the low natural frequency resonance must be avoided during the design optimization of the primary test loop. In a further study, a comparative study on the pressure pulsations inside the RCP will be conducted by experimental and numerical methods.

### NOMENCLATURE

- $H$: Nominal flow head, 111 m
- $n_a$: Nominal rotating speed, 1485 r/min
- $p$: Pressure, Pa
- $\bar{\Delta}$: mean amplitude of the pressure, Pa
- $\Delta p$: Pressure changed, $\Delta p = p - \bar{\Delta}$, Pa
- $\rho$: Water density, 996.2 kg/m$^3$ (28°C)
- $\rho g$: Where $\rho$ is the water density and $g$ is the acceleration due to gravity.
- $Z_a$: Impeller blade number, 4
- $Z_v$: Diffuser vane number, 7
- $f_s$: Sample frequency, 16,384 Hz
- $f_R$: Rotating frequency of impeller, $n_a/60$, Hz
- $f_{BPV}$: Blade-passing frequency, $Z_a f_R$, Hz
- $f_{VPV}$: Diffuser vane passing frequency, $Z_v f_R$, Hz
- $\Delta H$: Pressure pulsation is described as the water column, $\Delta H = \Delta p/\rho g$, m

### ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support given by the National Natural Science Foundation of China (U1808214), the China Scholarship Council (202006060155), and the support given by the Fundamental Research Funds in Dalian University of Technology (DUT20LAB125).

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**How to cite this article:** Zhou Q, Li H, Dong J, Zhong Z, Sun S. Experimental investigation on the unsteady pressure pulsation and vibration of a nuclear pump test loop. *Energy Sci Eng*. 2022;10:2877-2891. doi:10.1002/ese3.1176