INTRODUCTION

As the vital component of the nuclear reactor coolant pump (RCP), the impeller plays an indispensable role in driving the coolant in the primary loop in the nuclear power plant.\(^1,2\) The coolant circulation inherently brings flow fluctuation, especially pressure pulsation induced by the rotor-stator interaction,\(^3,4\) and therefore, flow-induced vibration exists, which has a considerable impact on the impeller. Moreover, for the RCP in the actual operation, the impeller operates at a high-temperature, high-pressure, high-radiation, and non-stop environment.\(^5,6\) Hence, it is urgently necessary to make a comprehensive understanding of the unsteady pressure pulsation and vibration characteristics of the RCP impeller.

At present, research both into the unsteady pressure pulsation and the vibration characteristic of the RCP impeller...
are rarely reported. Previous studies have already been focused to study the unsteady flow and pressure fluctuations in the aspects of numerical study and experiments of the RCP.\textsuperscript{7,8} Based on the dynamic pressure pulsation and Laser Doppler Velocimetry (LDV) measurements, Dan et al\textsuperscript{9} comprehensively elaborate the dynamic flow characteristics in an RCP. Long et al\textsuperscript{10} conducted the unsteady flow of a scaled model RCP with nonuniform inflow by mounting seven fast-response pressure transducers on the pump casing and outlet pipe. Zhang et al\textsuperscript{11} presented numerical research of the pressure pulsation characteristics induced by the rotor-stator interaction in an RCP, the amplitudes of pressure pulsation get the maximum between the rotor and stator. Pressure pulsation may cause severe vibration, which would result in some unexpected damages to the pump components.\textsuperscript{12,13} Some typical studies on the other pumps can be referred to. Egusquiza et al\textsuperscript{14} presented a dynamic analysis of a pump-turbine runner to determine the cause of unusual fatigue failure. Although no resonance was detected, the natural frequency of the runner is not much different from the excitation frequency of the pressure pulsation. Guo et al\textsuperscript{15} experimentally investigated the pressure pulsation of the impeller and the impeller vibration in a centrifugal pump. Resonance can be excited when a natural frequency of the impeller coincides with the sideband frequencies of the pressure pulsation. Special attention must be paid to the natural frequency of the impeller to avoid the hydraulic resonance for the high safety and stability requirements of the RCP in the nuclear power plant.

As for the natural frequency of the impeller, the modal analysis method is widely applied.\textsuperscript{16} The modal analysis can be divided into the experimental modal analysis (EMA) and finite element method (FEM), and the FEM can be validated by the EMA.\textsuperscript{17} Modal parameters play an important role in design optimization\textsuperscript{18} and reliability analysis,\textsuperscript{19} especially for the impeller with complex structures and high safety requirements.\textsuperscript{20} Wang et al\textsuperscript{21} conducted a modal analysis of a full-scale RCP impeller, and an improved design of the impeller was proposed to prevent hydraulic resonance. Due to the impeller submerged in a hostile fluid environment, modal properties are inevitably affected by the water,\textsuperscript{22} and the EMA becomes more challenging. Escaler et al\textsuperscript{23} and Valero et al\textsuperscript{24} conducted both the EMA and FEM of a reduced scale pump-turbine impeller with the impeller suspended inside the water and in the air. It is found that both the natural frequencies reduced and the characteristics of the coupled modes changed with the effect of the added mass from the water. The influence of the added mass should be concerned to determine the natural frequencies of the RCP impeller.

This study aims at investigating the unsteady pressure pulsation and the modal behavior of a scaled RCP impeller via experimental and numerical methods. The RCP numerical model was validated by a pressure pulsation experiment, and a detailed analysis of the pressure pulsation signal acting on the impeller was performed by the Welch method. The modal parameters of the impeller were obtained with the impeller suspended as a free body in the air as well as inside the water, and the added mass effect of the surrounding water was therefore analyzed. Finally, the pressure pulsations and modal parameters are combined to analyze the risk of the impeller resonance in the model pump.

### 2 | PRESSURE PULSATION ACTING ON THE IMPELLER

#### 2.1 | Numerical simulation

The pump used for this investigation is a model nuclear reactor coolant pump (on a scale of 1:2.5), as shown in Figure 1. The model RCP consists of an impeller with four blades, a radial diffuser with seven vanes, and an annular volute. Other main parameters of the model RCP are presented in Table 1. To obtain the pressure pulsation characteristics acting on the impeller, the RANS method\textsuperscript{25} and the Spalart-Allmaras turbulence model\textsuperscript{26} were employed to solve the Reynolds-averaged Navier-Stokes equations. The whole computational domain including the inlet and impeller, diffuser, volute, and outlet section in the entire flow field were meshed by the hexahedral element via the ICG model in the software Numeca. The total grid elements number is approximately 2.05 million on the balance of resource requirement and the computational accuracy. This grid has been validated in our previous study to explore the characteristics of the unsteady pressure pulsation in the flow passage of the diffuser.\textsuperscript{4} As shown in Figure 2, the value of $y+$ of the whole calculation model except the outlet pipe is lower than 10, which indicates the mesh generation is relatively reasonable. As shown in Figure 3, each channel of the diffuser was marked, and
eighteen monitoring points were arranged on the impeller blade, nine points set on the pressure surface, and nine on the suction surface. The nominal flow rate based on the practical operating condition is chosen for this calculation. The total pressure and total temperature at the inlet and the mass flow rate at the outlet are set as the boundary. In order to achieve adequate resolution of pressure signals, the time step size was set as $\Delta t = 3.6 \times 10^{-4}$ seconds. Nearly 50 impeller revolutions were calculated to enable periodic pressure pulsation results during the whole numerical simulation.

### 2.2 Experimental system

The pressure pulsation experiment was carried out in a closed-type test loop at the National Industrial Pump Quality Supervision and Inspection Center in Shenyang, China. The test bench meets the accuracy requirement, and the experimental equipment is shown in Figure 4. The test rig is mainly composed of the flow control valve, pressure pump, cavitation tank, surge tank, model pump, etc. As shown in Figure 5, the model RCP is driven by a three-phase asynchronous motor, of which the motor power and rated speed are 110 kW and 1490 r/min, respectively. The flow rate is measured by a magnetic flowmeter with an uncertainty of less than ±0.5%. To attain unsteady pressure pulsation signals for comparison with the numerical calculation at the same measuring point position, six piezoresistive pressure sensors, which are Endevco 8530C, were arranged at the entrance of two adjacent diffusers flow channel, as illustrated in Figure 6. The monitoring points named Ea, Eb, Ec, Fa, Fb, and Fc mounted on the same circumferential surface. The signals were recorded synchronously with a sample rate of 16 kHz and a sampling time of 60 seconds by the B&K data acquisition system.
2.3 | Simulation validation

The numerical model was validated with the pressure pulsation signals obtained at the inlet of the diffuser flow passage. All the pressure pulsation signals under the nominal flow rate were normalized by the pressure coefficient,\(^27\) which was defined by the transient pressure pulsation \(P\), the mean of the pressure pulsation \(\overline{P}\), the water density \(\rho\), and the circumferential velocity at impeller periphery \(u\), as follows:

\[
C_p = \frac{P - \overline{P}}{0.5 \rho u^2}
\]  

The Welch method was applied to obtain the frequency domain features of the pressure pulsation. The power spectrum density was computed by partitioning each time signal into segments with a 50% overlapping, averaging the estimates of each segment, filtered with a Hanning window to avoid the spectral leakage. The power spectrum density estimation was determined from the following equation:

\[
P_x(f) = \frac{1}{N} \sum_{k=0}^{N-1} x(t) \times w(t) \times e^{-j2\pi kf/f_s},
\]

where \(x(t)\) is the time domain signal of the pressure pulsation, \(w(t)\) is the Hanning window function, and \(f_s\) is the sampling frequency.

Comparison of the pressure spectrum at the nominal flow rate between the simulation and experiment is as illustrated in Figure 7. Pressure peaks corresponding to the blade-passing frequency \(f_{BPF}\) and its harmonic frequencies \(2f_{BPF}, 3f_{BPF},\) and \(4f_{BPF}\) are easily captured in the numerical and experimental results. Obviously, the frequency component of the pressure pulsation is consistent while the pressure pulsation frequency components are closely associated with the position of the measuring points. The dominant frequency at point Ea and Eb is \(f_{BPF}\) while \(2f_{BPF}\) at Ec. The amplitude difference between simulation and experiment may be caused by the manufacturing errors, as the diameter of the sensor is about 3.86 mm in the experiment while it is just a point in the simulation.\(^8\) Moreover, the trend variation of the pressure pulsation amplitude is consistent although the error exists. As for the pressure pulsation prediction, the numerical results and the experimental results were in good agreement. It can be considered that the numerical results can be applied to explore the pressure pulsation characteristics acting on the impeller’s blade.

2.4 | Pressure pulsation acting on the impeller blade

The RCP impeller operating even at the nominal flow rate is subject to pressure pulsation resulting from the rotor-stator interaction and induces its vibration. Obtaining the characteristics of the pressure pulsation acting on the blade is of great significance for the design and optimization of the impeller. Figure 8 shows the spectrum analysis of pressure pulsation acting on the impeller blade at the nominal flow rate. The monitoring points at the pressure and suction surface are located at the same position but on different sides. The rotating frequency of the impeller \(f_0\), the double blade-passing frequency \(2f_{BPF}\), the vane passing frequency \(f_{VPF}\), and its harmonics can be easily captured. Notably, the dominant frequency components of the pressure pulsation are closely associated with the position of the measuring points. The possible reason that accounts for the different dominant frequencies is associated with the intensive rotor-stator interaction and the rotation of the impeller itself. When the impeller blades pass
across their wakes, a hydraulic force caused by the RSI gives regular periodic excitation to the impeller, it consists of various harmonics with the vane passing frequency \(f_{VPF}\) and its higher harmonics.\(^1\) From the dominant frequency comparison of the pressure pulsation acting on the impeller, either at the pressure surface or at the suction surface the dominant frequency is \(f_{VPF}\) near the outlet while \(f_R\) near the inlet of the impeller passage. In the middle of the impeller blade, \(f_{VPF}\) is the dominant frequency on the pressure surface while \(f_R\) on the suction surface. Not only the dominant frequency components of the pressure pulsation acting on the impeller blade but also the corresponding amplitudes are affected by the RSI and the rotation of the impeller itself.

Figure 9 indicates the characteristic frequency amplitudes comparison of the pressure pulsation signal over all the monitoring points. In general, the pressure pulsation acting on the blade’s pressure surface is more intense than the suction surface, and the pressure pulsation near the impeller inlet is less intense than the impeller outlet. The highest magnitude of the \(f_R\) locates at P7 while the lowest at P9 on the impeller inlet when the impeller drives the coolant. The pressure pulsation near the impeller outlet is more affected by the RSI, and much more influence is on the pressure surface, as is seen from the amplitude comparison of vane passing frequency \(f_{VPF}\). The amplitudes of the \(f_R\) are always higher than that of the \(2f_{BPF}\) of all the measuring points, while the amplitudes of the \(f_{VPF}\) are not. The amplitudes of the \(2f_{BPF}\) on the pressure surface are higher than that on the suction surface near the impeller outlet, which also indicates the influence of the RSI is more on the pressure surface.

### 3 MODAL ANALYSIS OF THE IMPELLER

#### 3.1 Experimental modal analysis

The reduced scale RCP impeller is a whole body with four blades. As shown in Figure 10, the modal tests were carried out under free-free conditions with the impeller suspended as a free body by a flexible string, both in the air and submerged inside the water. Figure 11 shows the modal test system. The hammer with a nylon impact cap was applied to excite the impeller, and six piezoelectric accelerometers with low-mass and high-frequency responses were used to measure the vibration response. According to the structural characteristics and geometry size of the impeller, the excitation points are fixed to the impeller while accelerometers roved over the whole impeller. Signals of the impact force and accelerometer response were recorded by the data acquisition instrument. The frequency response functions (FRFs) between the induced response acceleration and the excitation force signals were calculated, and the modal parameters were extracted via the PolyMAX modal identification algorithm by the Modal Analysis Software. Both modal test procedures were almost the same, except some essential waterproof measurements and the same impeller depth ensured when the impeller submerged inside the water.

#### 3.2 Numerical modal analysis

The numerical modal analysis is a kind of theoretical modeling process, which mainly uses the finite element method...
to discrete the vibration structure, establish the mathematical model of system eigenvalues, and solve the system eigenvalues and eigenvectors with various approximate methods. The numerical modal analysis of the impeller carried out with the same boundary conditions in the modal experiments, the finite element model of the impeller is shown in Figure 12. The modal and modal acoustics modules of the ANSYS Workbench platform were applied to determine the impeller modal characteristics. The impeller in the air was meshed by the patch conforming method with adaptive tetrahedral elements. The impeller material is Aluminum alloy, and the modal behavior is solved by the subspace method. When the impeller submerged inside the water, the solid domain of the impeller was set to be completely surrounded by the water liquid. The fluid-solid interfaces were created to identify the interfaces between the structural impeller and the surrounding water. The pressure of the water domain model faces was defined zero as the acoustic boundary conditions, and then, the acoustic modal behavior was solved by the unsymmetric method.

3.3 | Modal validation

The number of nodal diameters (ND) is applied to classify and validate the impeller modes between the numerical and experimental results. The nodal diameter describes the actual number of observable waves around the structure. As illustrated in Figures 13 and 14, whether the impeller is suspended
in air or submerged inside water, the numerical and experimental modal shape results are consistent. The first mode of the impeller corresponding to the 2ND modal shape, and

the second mode performed the 2ND modal shape as well, but the position of the nodes and nodal lines has changed, as the impeller with a rotational periodic symmetric structure, which is called 2-2ND. Following the third mode is the 1ND modal shape and the 2-1ND pattern as the fourth-order modal shape.

In a nuclear reactor coolant pump, a range of impeller natural frequency can be predicted during the design phase for stable operating conditions using available numerical techniques. Table 2 summarizes the experimental and numerical modal results of the impeller. Good agreement was obtained, and the maximum difference of the natural frequencies was 4.11% in air and 3.59% in water, which meets the accuracy requirement of practical engineering. Moreover, the natural frequency can also be applied to estimate the added mass effect on the impeller. The reduction in the impeller natural frequencies was between 31.63% and 37.77% for the corresponding mode shape from the experimental results. A similar added mass effect can also be obtained from the numerical results.

4 RESONANCE ANALYSIS OF THE IMPeller

The impeller is excited by the periodic pressure pulsation due to the rotor-stator interaction (RSI) and the impeller itself
rotation. Combining this current research and our previous work, the pressure pulsation induced by the RSI near the impeller outlet is the blade-passing frequency (\( f_{BPF} \)) and its higher harmonics, the pressure pulsation acting on the impeller blade is the rotating frequency of the impeller (\( f_R \)), the double blade-passing frequency (\( 2f_{BPF} \)), the vane passing frequency (\( f_{VPF} \)), and its harmonics. A potentially strong resonance may occur if the frequency of excitation is equal or near to the natural frequency of the impeller and the structural mode matched.

When the impeller is subjected to flow-induced forces, its vibration characteristics change. The added mass effect from the water can modify considerably the natural frequencies of the impeller. However, the added mass effect during
TABLE 2  Modal parameters (Hz)

| Order | $f_{\text{exp. air}}$ | $f_{\text{num. air}}$ | $\Delta_{\text{air}}$ | $f_{\text{exp. water}}$ | $f_{\text{num. water}}$ | $\Delta_{\text{water}}$ | $\delta_{\text{exp}}$ | $\delta_{\text{num}}$ |
|-------|------------------|------------------|--------------------|------------------|------------------|--------------------|------------------|------------------|
| 2ND   | 1303.7           | 1250.1           | 4.11%              | 855.7            | 843.7            | 1.40%              | 34.37%           | 32.51%           |
| 2-2ND | 1483.7           | 1453.1           | 2.06%              | 923.4            | 956.5            | −3.59%             | 37.77%           | 34.18%           |
| 1ND   | 2325.1           | 2389.4           | −2.76%             | 1572.4           | 1615.3           | −2.73%             | 32.37%           | 32.40%           |
| 1-2ND | 2336.5           | 2391.1           | −2.34%             | 1597.4           | 1617.1           | −1.23%             | 31.63%           | 32.37%           |

Note: Deviation of numerical value (natural frequency) from the experimental value, $\Delta = 1 - (f_{\text{num}}/f_{\text{exp}})$.

A transient operating condition such as a start-stop is completely unknown now. The added mass might be significant in the case of a rapid change in the flow field due to an accelerating/decelerating impeller structure. The change in impeller speed also changes the frequency of forced excitation. The natural frequencies are generally assumed to be higher under transient conditions than under steady-state operating conditions. In this research, the first natural frequency of the impeller inside water is 855.677Hz, which is far greater than the potential exciting frequency. It can be considered that there is no risk of impeller resonance.

5 | CONCLUSION

The pressure pulsation of the impeller blade and the modal properties of the impeller were investigated in a nuclear coolant pump. The main conclusions are as follows.

The pressure pulsation acting on the impeller is mainly composed of the impeller rotating frequency, the vane passing frequency, and the double blade-passing frequency. Pressure pulsation acting on the blade’s pressure surface is more intense than that on the suction surface.

Due to the added mass effect of the water, the same mode shapes obtained in the air can also be obtained in water but with a lower frequency. Combined with the pressure pulsation acting on the impeller and the modal properties, there is no risk of impeller resonance.

Finally, it is expected that the present work will provide a different view for the optimum design of the impeller, especially avoiding the hydraulic resonance in the reactor coolant pump. In further work, some fundamental research to make a good understanding of the added mass effect on the natural frequency of the impeller will be conducted and the temperature effect will be considered as well.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Major Science and Technology Project in Liaoning Province (2019JH11/1010001951576125) and the Fundamental Research Funds for the Dalian University of Technology (DUT20LAB125).

REFERENCES

1. Ni D, Yang M, Gao B, Zhang N, Li Z. Flow unsteadiness and pressure pulsations in a nuclear reactor coolant pump. Strojniški Vestnik J Mech Eng. 2016;62(4):231-242.
2. Yun L, Dezhong W, Junlian Y, Yaoyu H, Hongjuan R. Numerical investigation on the unsteady characteristics of reactor coolant pumps with non-uniform inflow. Nucl Eng Des. 2017;320:65-76.
3. Pei J, Wang W, Pavesi G, Osman MK, Meng F. Experimental investigation of the nonlinear pressure fluctuations in a residual heat removal pump. Ann Nucl Energy. 2019;131:63-79.
4. Zhou Q, Li H, Pei L, Zhong Z. Research on non-uniform pressure pulsation of the diffuser in a nuclear reactor coolant pump. Nucl Eng Technol. 2021;53(3):1020-1028.
5. Gong CM, Shen H, Yao QZ. Theoretical and numerical modal analysis for nuclear coolant pump and its scaled rotor system. Appl Mech Mater. 2010;44-47:985-991.
6. Zhang JG, Yue Z. Stress analysis of the canned nuclear coolant pump based on FSI. International Conference on Nuclear Engineering. 2014. 2014.
7. Zhang Y, Yang M, Ni D, Zhang N, Gao B. Particle image velocimetry measurement of complex flow structures in the diffuser and spherical casing of a reactor coolant pump. Nucl Engi Technol. 2018;50(3):368-378.
8. Ni D, Yang M, Gao B, Zhang N, Li Z. Experimental and numerical investigation on the pressure pulsation and instantaneous flow structure in a nuclear reactor coolant pump. Nucl Eng Des. 2018;337:261-270.
9. Ni D, Zhang N, Gao B, Li Z, Yang M. Dynamic measurements on unsteady pressure pulsations and flow distributions in a nuclear reactor coolant pump. Energy. 2020;198:117305.
10. Long Y, Wang D, Yin J, Hu Y. Experimental investigation on the unsteady pressure pulsation of reactor coolant pumps with non-uniform inflow. Ann Nucl Energy. 2017;110:501-510.
11. Zhang X, Wang P, Ruan X, Xu Z, Fu X. Analysis of pressure pulsation induced by rotor-stator interaction in nuclear reactor coolant pump. Shock Vibration. 2017;2017:1-18.
12. Tanaka H. Vibration behavior and dynamic stress of runners of very high head reversible pump-turbines. Int J Fluid Machin Syst. 2011;4(2):289-306.
13. Khalifa AE, Al-Qutub AM, Ben-Mansour R. Study of pressure fluctuations and induced vibration at blade-passing frequencies of a double volute pump. Arab J Sci Eng. 2011;36(7):1333-1345.
14. Egusquiza E, Valero C, Huang X, Jou E, Guardo A, Rodriguez C. Failure investigation of a large pump-turbine runner. Eng Fail Anal. 2012;23:27-34.
15. Guo S, Maruta Y. Experimental investigations on pressure fluctuations and vibration of the impeller in a centrifugal pump with vaned diffusers. JSME Int J Ser B. 2005;48(1):136-143.
16. Ewins DJ. Modal Testing: Theory, Practice and Application, 2nd edn. Hertfordshire: Research Studies Press Ltd.; 2000.
17. Zhu WD, Liu JM, Xu YF, Ying HQ. A modal test method using sound pressure transducers based on vibro-acoustic reciprocity. J Sound Vib. 2014;333(13):2728-2742.
18. More KC, Dongre S, Deshmukh GP. Experimental and numerical analysis of vibrations in impeller of centrifugal blower. SN Applied Sciences. 2020;2(1),http://dx.doi.org/10.1007/s42452-019-1853-x
19. Ashri M, Karuppanan S, Patil S, Ibrahim I. Modal analysis of a centrifugal pump impeller using finite element method. MATEC Web Conf. 2014;13:04030.
20. Egusquiza E, Valero C, Presas A, Huang X, Guardo A, Seidel U. Analysis of the dynamic response of pump-turbine impellers. Influence of the rotor. Mech Syst Sig Process. 2016;68-69:330-341.
21. Wang J, Wang P, Zhang X, Ruan X, Xu Z, Fu X. Research of modal analysis for impeller of reactor coolant pump. Appl Sci. 2019;9(21):4551.
22. Rodriguez CG, Egusquiza E, Escaler X, Liang QW, Avellan F. Experimental investigation of added mass effects on a Francis turbine runner in still water. J Fluids Struct. 2006;22(5):699-712.
23. Escaler X, Hütter JK, Egusquiza E, Farhat M, Avellan F. Modal behavior of a reduced scale pump-turbine impeller. Part I: Experiments. IOP Conf Ser Earth Environ Sci. 2010;12:012116.
24. Valero C, Huang X, Egusquiza E, Farhat M, Avellan F. Modal behavior of a reduced scale pump turbine impeller. Part II: Numerical simulation. IOP Conf Ser Earth Environ Sci. 2010;12:012117.
25. Fujun W. Research progress of computational model for rotating turbulent flow in fluid machinery. Trans Chin Soc Agric Machin. 2016;47(2):1-14.
26. Spalart P, Allmaras S. A one-equation turbulence model for aerodynamic flows. 1992;439.
27. Barrio R, Parrondo J, Blanco E. Numerical analysis of the unsteady flow in the near-tongue region in a volute-type centrifugal pump for different operating points. Comput Fluids. 2010;39(5):859-870.
28. Trivedi C, Cervantes MJ. Fluid-structure interactions in Francis turbines: a perspective review. Renew Sustain Energy Rev. 2017;68:87-101.

How to cite this article: Zhou Q, Zhao X, Pei L, Li H. Investigation on pressure pulsation and modal behavior of the impeller in a nuclear reactor coolant pump. Energy Sci Eng. 2021;00:1–10. https://doi.org/10.1002/ese3.904