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An Intelligent Vibration System for Concrete in Nuclear Power Engineering

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Abstract: In nuclear power engineering, the quality requirements for concrete are extremely stringent. Concrete structures must exhibit high durability to withstand the effects of nuclear radiation, chemical corrosion, and environmental changes. In particular, nuclear power projects impose higher design standards and safety requirements regarding concrete density. Traditional manual vibration and visual inspection methods are difficult to ensure the required level of concrete compaction. This paper presents an intelligent vibration technology for concrete in nuclear power engineering to enhance construction quality and efficiency. By integrating intelligent sensors, control systems, and data processing algorithms, the technology enables real-time monitoring and evaluation of the vibration process. Results show that intelligent vibration technology effectively ensures the density and uniformity of concrete in nuclear power engineering, thereby improving structural safety and reliability.

Keywords: Nuclear Power Engineering; Intelligent Vibration System; Smart Sensor; Density; Concrete construction

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1. Introduction

Nuclear power engineering projects (such as reactor buildings) carry extremely stringent requirements for concrete quality, as the safety of nuclear power plants during operation is directly related to public safety and the ecological environment. Nuclear power projects are often built near the coast, where salt mist corrosion is severe. Moreover, reactor buildings consist of large volumes of concrete, which require exceptionally high strength and impermeability standards (e.g., C60P8), distinguishing them significantly from civil engineering projects. The concrete structures in nuclear power engineering must possess enhanced durability to withstand the impacts of nuclear radiation, chemical corrosion, and environmental changes, and they must comply with higher design standards and safety requirements regarding the compactness, uniformity, and strength of the concrete.

As the most fundamental material in civil engineering, the quality of concrete construction is directly related to the overall quality of the building structure, with pouring and vibrating playing a crucial role in construction quality [1]. Insufficient vibration can lead to the formation of honeycombs, voids, and cold joints in hardened concrete, while excessive vibration may result in the segregation and uneven distribution of aggregates [2, 3]. In nuclear power engineering, concrete vibration is a key process to ensure that the concrete is fully compacted, directly influencing the sealing and load-bearing performance of the nuclear power plant structure. Insufficient or improper vibration can lead to defects in concrete quality and even pose risks of nuclear leakage. Traditional vibration techniques, which rely on manual labour and lack intelligent control and real-time feedback, struggle to meet the high standards required for concrete quality in nuclear power projects. There are significant quality defects associated with manual vibration, and rectifying these defects post-formation can be costly [4]. Research shows that determining the optimal compaction solely based on the cessation of bubbles on the surface of concrete is not feasible, as it may lead to concrete segregation and compromise quality. Therefore, more online measurement methods should be developed rather than solely relying on surface bubble observation [5]. Currently, intelligent vibration technology includes methods based on vibration depth and location, as well as techniques based on vibration time, all of which enhance vibration quality to a certain extent [6–14]. Therefore, advancing intelligent vibration technology can fundamentally address the fluctuations in concrete construction quality in nuclear power engineering, making it an inevitable choice for the sector to embrace intelligence and high reliability, and serves as an important technical pathway for achieving green construction in line with the ‘dual carbon’ goals.

2. Theoretical foundation

2.1. Principle of concrete vibration

Generally, freshly mixed concrete belongs to the Bingham fluid, and when the shear stress exceeds the static yield stress of the concrete, the concrete flows, accompanied by the sinking of the aggregate and the upward movement of the enveloping bubbles [15, 16]. From an energy point of view, the energy generated by the vibrator travels in the form of vibrational waves of a certain amplitude and frequency. The greater the energy, the greater the excitation force provided by the vibration rod to the concrete, and the better the concrete flow effect. Within the effective range of vibration, the shear force exceeds the yield stress, the fluidity of the concrete is enhanced, the aggregate sinks, and the bubbles contained in the package float or are vibrated and discharged, so that the slurry is more fully filled and the purpose of compacting the concrete is achieved [16].

2.2. The principle of intelligent vibration compaction technology

The intelligent vibration compaction technology integrates sensors, automated control, and artificial intelligence algorithms to achieve dynamic monitoring, parameter optimization, and precise execution in the concrete vibration process. Its core principles include multi-source data perception, real-time monitoring, and intelligent decision-making. Through the fully integrated process of “perception-analysis-execution-verification”, intelligent vibration compaction technology transforms traditional experience-based extensive processes into data-driven precise control, providing innovative solutions for the synergistic optimization of quality, safety, and efficiency in major high-standard projects such as nuclear power.

3. Research on key technologies for intelligent vibration

3.1. Parameter optimization for vibration

The vibration parameters directly affect the compactness, uniformity and construction efficiency of concrete, and the core parameters include vibration time, vibration frequency, amplitude, insertion depth, and vibration radius. Vibration parameter optimization includes multi-source data acquisition, fusion, and parameter optimization algorithms. The former is used to build a dynamic digital twin of the concrete state, the latter employs machine learning and reinforcement learning to train a neural network with historical construction data, predict the parameter requirements under different working conditions, and dynamically adjust the vibration parameters in conjunction with trial-and-error learning to achieve the goal of maximizing compactness.

Based on the real-time data from the sensor, PID control or fuzzy logic is utilized to dynamically fine-tune the parameters, such as automatically extending the vibration time or increasing the frequency when a certain area is detected to be insufficient. The system includes an adaptive learning mechanism, which continuously updates the optimization model through online learning to adapt to changes in the concrete ratio or environmental interference. Furthermore, the optimization experience of vibration parameters from other projects (such as dams and bridges) can be transferred to nuclear power scenarios, and the generalization ability of the model can be enhanced through transfer learning.

3.2. Research and development of vibration system

An intelligent vibration system comprises hardware devices and software control module, as shown in **Figure 1**. The hardware architecture consists of a vibration execution unit and a sensor system, while the software and control module is made up of an intelligent decision-making system and a human-computer interaction interface. The intelligent vibration rod employs piezoelectric ceramic or electromagnetic drive technology, a planetary excitation mode, and high-frequency and low-amplitude vibration, which can actively mitigate the risk of concrete segregation. The rod body is embedded with vibration sensors and fiber grating sensors, which can obtain the main frequency, amplitude, and surface pressure of the vibration rod, and monitor the vibration status (compactness, fluidity, or vibration resistance) of the concrete in real time.

The accelerometer gathers data from the accelerometer, the active power collector gathers active power when the rod vibrates, the voltage stabilizer source is responsible for supplying power to the active power collector, and the depth is obtained by using the positioning module or setting a scale mark on the rod body. The PC is charged with processing the collected data, using the data as input for the energy transfer model, and ultimately achieving the visualization of concrete energy distribution on the host computer software.

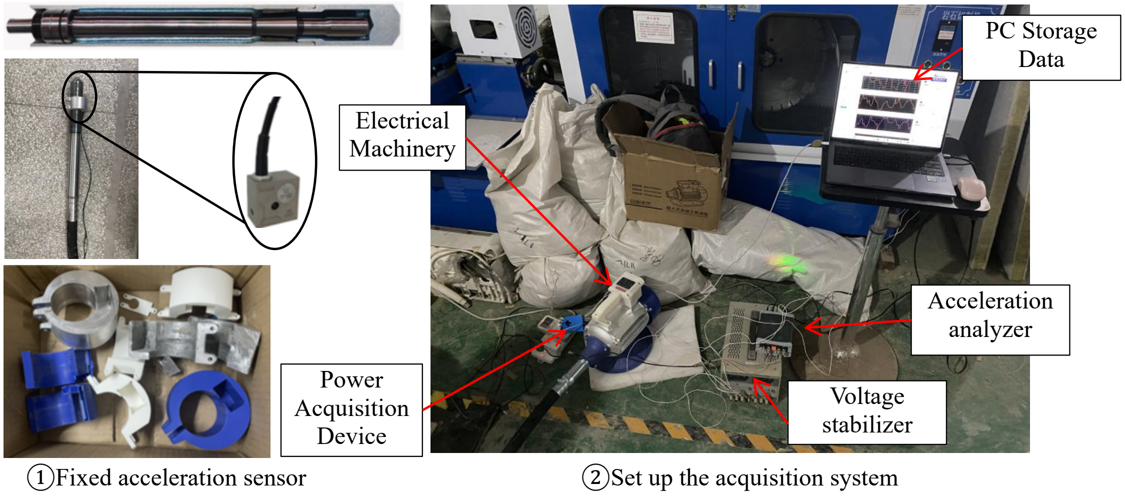


Figure 1. Composition of intelligent vibration system

3.3. Monitoring and evaluation of the stirring process

The intelligent vibration process monitoring and evaluation aims to ensure that the concrete vibration quality meets the high standards of nuclear power engineering through multi-dimensional data collection, real-time analysis, and intelligent decision-making. At present, the sensor network is mainly for vibration monitoring, environmental perception, and equipment status monitoring, which is used to monitor the vibration, pressure change, and temperature change of concrete in real time. The front-end data is preprocessed through the data acquisition module, the data is transmitted to the monitoring center in real time by wired or wireless communication, and the central processing unit analyses the collected data, identifies the vibration state of the concrete, and judges whether the concrete meets the predetermined density requirements by comparing with the set threshold.

As shown in **Figure 2**, the monitoring platform displays the processed data to the operator in a graphical interface, enabling the operator to diagnose in real time. If a vibration parameter is detected that deviates from the preset standard, the system automatically sends a warning or adjustment signal. According to the data feedback, the monitoring system dynamically adjusts the concrete vibration parameters through data-driven and algorithmic models to optimize the vibration effect.

Figure 2. Intelligent concrete vibration monitoring platform

3.4. Evaluation methods for concrete density

Accelerometers, acceleration analyzers, power collection instruments, current transformers, and other equipment were used to obtain specific data on concrete vibration [17]. Based on **Figure 3**, a model for evaluating the compactness of concrete vibration was established using the energy absorption rate calculation method for concrete per unit mass, and the mathematical relationship between vibration parameters and concrete compactness was derived to predict the optimal parameter combination [18]. As shown in **Figure 4**, the energy absorption value is calculated by multiplying the energy absorption rate by the vibration duration, while the range of concrete compaction energy is determined through compressive strength tests of standard specimens, as shown in **Table 1**, for the experiment, C30 concrete from a nuclear island facility was selected, and real-time monitoring of the concrete status during the vibration process was conducted to obtain the distribution of energy absorption rate and energy absorption value per unit mass of concrete under these working conditions.

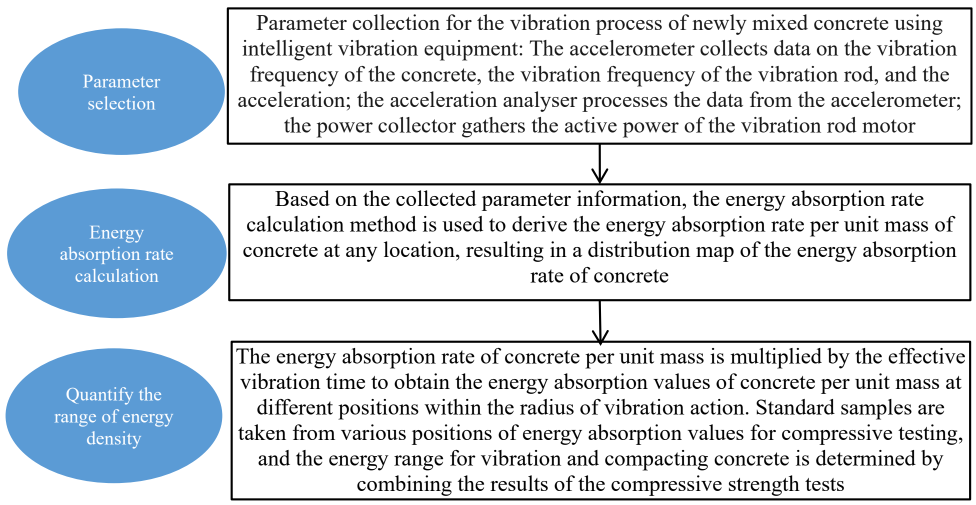
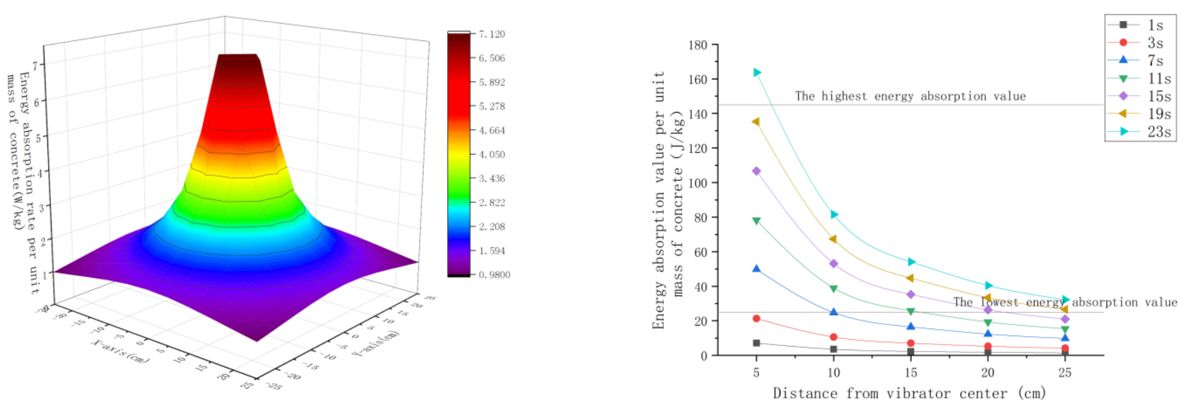


Figure 3. Evaluation process for the effects of vibration and compaction [17]



a. Energy absorption per cm²　　　　b. Energy absorption values per cm²

Figure 4. Analysis on energy absorption

Table 1. List of concrete mix ratios for a nuclear island plant

No.	Strength level	Mixing ratio of raw materials information(kg.m³)						Degree of slump(mm)	Remarks
		Water	Cement P.N	Fly coal ash	Sand	Crushed stone	Water reducing agent		
1	C30	165	264	87	776	1071	3.69–4.74	160 ± 30	5–25 mm Crushed stone

4. Conclusion

This paper integrates advanced sensors, data processing technologies, and automated control systems to optimize vibration parameters and processes. By precisely controlling key parameters during the vibration process, the density and uniformity of concrete in nuclear power engineering can be effectively ensured. The work lays a solid theoretical foundation for implementing intelligent concrete vibration techniques in nuclear power projects.

However, there are still some limitations in this work. The experimental data were obtained in a controlled laboratory setting and have not yet been validated in actual nuclear power engineering projects. Additionally, there are issues regarding the low integration of intelligent devices and the insufficient functionality of the intelligent monitoring system. Future research will address these shortcomings. Furthermore, with advancements in AI, smart construction, and 3D acoustic imaging technology, intelligent vibration systems are expected to evolve toward nano-level defect detection and comprehensive lifecycle performance monitoring. These developments have the potential to systematically resolve the efficiency and quality challenges faced by traditional concrete processes.

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Disclosure statement

The authors declare no conflict of interest.

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