Research and application of a new type of aqueduct concrete non-destructive inspection robot based on the principle of coherent frequency

HUANG Tao¹, YAO Qifa², ZHAO Xiaopeng³, SONG Wenjie⁴
¹China Institute of Water Resources and Hydropower Research, State Key Laboratory Simulation and Regulation of Water Cycle in River Basin Beijing, China
²Beijing Tong Du Engineering Geophysics Limited Beijing, China
³Beijing Tong Du Engineering Geophysics Limited Beijing, China
⁴China Institute of Water Resources and Hydropower Research, State Key Laboratory Simulation and Regulation of Water Cycle in River Basin Beijing, China

Abstract. The concrete aqueduct has some quality problems such as lacuna and cavity during construction or operation, which seriously affects the safety of aqueduct operation. How to quickly detect the defects of aqueduct is of great significance to provide the basis for the repair and reinforcement of aqueduct. In this paper, based on the coherent frequency method, the automatic walking robot device for concrete nondestructive testing is integrated and assembled. Through wireless communication, the automatic excitation, acquisition and imaging of elastic wave are completed, so as to realize the rapid detection of uniformity and compactness defects of aqueduct concrete structure. Through the test and engineering demonstration application, the detection results are reliable, and the detection efficiency is improved by more than 50%. And the follow-up improvement plan of the system hardware should strengthen the maneuverability of the car, realize precise positioning, strengthen the energy of the seismic source, and improve the overall reliability of the system.

1. Preface
With the development of my country's economy and society, my country's water demand is increasing day by day, and the contradiction in the supply of water resources is also increasing [1-3]. In order to solve the problem of the unreasonable distribution of water resources in my country [4,5], tens of thousands of different standards and types of trans-regional and trans-basin water resources optimization projects have been built, and the aqueduct is an indispensable part of the water resources optimization project of hydraulic structures [6-9]. Due to the severe working conditions of hydraulic structures, along with the increase in service time, a large number of reinforced concrete aqueducts have experienced concrete deterioration, steel corrosion and other diseases, which have become a major hidden danger that threatens the safety of people’s lives and properties [10-16]. In the past practice of repairing and
strengthening aqueduct projects in my country, some projects began to formulate and implement repair plans without making a positive judgment on the scope, extent and development trend of concrete defects. Due to the poorly targeted repair measures and the lack of accurate damage assessment of the current situation of concrete, the situation of "broken repairs, repaired and broken" often occurs. Therefore, defect detection and diagnosis for the disease status of the aqueduct is an important research topic. In order to solve the increasingly arduous tasks of non-destructive inspection of concrete aqueducts and improve inspection efficiency, in view of the harsh environment of concrete aqueduct surface inspection, combined with intelligent robots and non-destructive inspection technology, a new automated non-destructive inspection robot for concrete aqueducts is designed.

2. Non-destructive inspection robot architecture of aqueduct concrete

2.1. Overall system design

Based on the machine walking platform, the aqueduct concrete nondestructive testing robot, completes the automatic excitation, acquisition and imaging of elastic wave through wireless operation, so as to realize the rapid detection of uniformity, compactness and strength defects of aqueduct concrete structure, as shown in Fig. 1. The system consists of two parts: hardware system and software system. The hardware includes the vehicle-mounted platform subsystem, the seismic source subsystem, the acquisition subsystem, and the wireless control subsystem. The software includes main functions such as walking control and automatic acquisition, data processing, etc., which is installed in the handheld PAD. When the system is in use, the handheld PAD first establishes a wireless connection with the robot through WIFI, and then operates the robot to walk through the software, and automatically excites and collects while walking. After the collection, data processing and analysis are performed immediately, the detection profile results are displayed in real time, and the data is automatically saved. Data analysis and processing and imaging can be performed again after the on-site acquisition.

![Non-destructive inspection robot of aqueduct concrete](image)

Fig.1  Non-destructive inspection robot of aqueduct concrete

2.2. Hardware structure of the system

The hardware structure of nondestructive testing robot system for aqueduct concrete is shown in Fig. 2. The system consists of four subsystems: walking platform subsystem, source subsystem, acquisition subsystem and communication subsystem.
Walking platform subsystem. There are two functions of the walking platform subsystem. On the one hand, it is to realize the automatic walking of the system; On the other hand, it is the platform of other hardware subsystems.

The walking platform subsystem is a robot platform with four-wheel 45 degree omni-directional wheel train. It uses four-wheel drive omni-directional wheel, and can realize special movements such as translation, rotation, translation and rotation.

The platform chassis adopts integral aluminum alloy casting process, which uses four high-power hollow cup motors as the drive, and is equipped with four axis servo driver, which supports can bus and RS232 interface.

The system has the following characteristics: 1) Free movement in all directions: The four-wheel omnidirectional structure enables the robot to move in any direction in the plane, accompanied by rotation; 2) Suspension system: With the rocker suspension structure, the four wheels of the robot can make good contact with the ground and output power. When passing through the uneven ground, the robot has a strong passing performance. It can effectively reduce the vibration when passing through the unsmooth ground; 3) Integral forming chassis: The platform chassis is made of aluminum alloy, with good structure, high strength and high rigidity. In order to ensure the high-precision four-wheel relative position relationship, the machining center is processed once. It avoids the disadvantages of poor connection precision, large cumulative error, poor strength and rigidity of the steel plate assembly robot; 4) Coreless DC Servo Motor: Four high-power coreless DC servo motors achieve high power density, high torque and fast speed response. The motor is equipped with a precision planetary reducer and a 500-line encoder; 5) Four axis servo driver: The four axis servo driver makes the coreless servo motor give full play to its characteristics and make the motor have a good characteristic curve. The user can accurately and quickly control the motor speed without being affected by the load and road surface changes, making the robot run accurately and reliably.

Seismic source subsystem. The seismic source platform subsystem collects the rotating impact structure, and the rotating impact mechanism is controlled by a servo motor. The impact mechanism generates an impact at a specified speed.

The servo motor of the seismic source subsystem is a fully digital AC servo integrated machine based on a 32-bit DSP platform:

1) Single group DC power supply; 2) Support optocoupler isolated pulse, direction control input and alarm output; 3) The series adopts 485 bus and supports MODBUS_RTU protocol; 4) Built-in single-axis motion control function, supporting three modes of point-to-point position control, speed control and synchronous cycle position control; 5) Using magnetic field position detection technology to achieve rotor orientation, with better anti-dust and anti-vibration capabilities.
Acquisition subsystem. The acquisition sub-system is responsible for receiving the signal which is generated by the seismic source and performs digital acquisition. The transmission adopts wireless WIFI mode. The specific performance is shown in Table 1.

| Geophone            | Acquisition card |               |
|---------------------|------------------|---------------|
| numbers             | 6                | sampling rate |
| type                | acceleration     | 1Hz~156KHz    |
| frequency band      | 1~16KHz          | AD digits     |
|                     |                  | 24            |
|                     |                  | Number of channels |
|                     |                  | 16            |
|                     |                  | Communication mode |
|                     |                  | WIFI          |

Communication sub-system. The communication subsystem is used for the communication between the host computer and various subsystems such as walking, seismic source, acquisition, etc.

Subsystem adopts multi-functional industrial-grade wireless serial port gateway, which can simultaneously communicate in various ways. Among them, the seismic source subsystem is adopted with RS232 serial communication, and the walking subsystem is adopted with RS232 serial communication, and the acquisition subsystem is adopted with RJ45 Ethernet TCP/IP protocol communication.

2.3. System software structure
The system software system consists of the main system and three subsystems of field acquisition, signal processing, and computational imaging. The main system is responsible for the creation and storage of survey line data. The system organizes the data according to the survey line, all data is placed in the designated directory, and the structure is shown in Fig. 3. The project file is used to save the relevant parameters and imaging data of the current survey line. The signal data is divided into raw data, preprocessed data and reflection gather data.

The data returned by the acquisition subsystem is saved as the original signal, and then the data is preprocessed according to the processing process and parameters defined in the preprocessing parameter definition file to obtain the preprocessed data file, and then the channel is extracted to form the CMP according to the reflection seismic common center gather extraction method data file.

The above three sets of data are automatically generated and saved by the main system. The data format is a custom non-standard SGY format. A single file can save 120 shots of data. The system automatically maintains the number of data files.
The field acquisition subsystem is used for communication, control and data transmission with the walking platform, seismic source, acquisition and other subsystems. It can realize walking, excitation and acquisition at the same time, and can realize real-time imaging. The signal processing subsystem can realize various seismic signal processing functions such as band pass/band trap, excision, delay correction, etc., which can be performed in real time during the acquisition process, or can be reprocessed when the data is returned after the acquisition is completed. The computational imaging subsystem is used for computational imaging, which can be performed in real time during the acquisition process, or can be reprocessed when the data is returned after the acquisition is completed, as shown in Fig. 4. The system supports multiple imaging methods such as reflection CMP stacking method and coherent frequency method.

3. Key technology for concrete inspection of aqueduct

3.1. Principle of Coherent Frequency Detection
The quality inspection of the aqueduct concrete uses sound wave scattering technology to determine the interface position and reflection coefficient according to the frequency of the coherent superposition of multiple reflections between the upper and lower interfaces [17]. This technology is based on the
scattering theory, comprehensively using directional filtering technology, velocity scanning technology, synthetic aperture imaging technology and coherent frequency imaging technology to realize the detection of engineering fine structure. It has the characteristics of high resolution, good reliability, and intuitive images, which is especially suitable for the needs of engineering structure inspection [18]. For the same engineering material, when there is unevenness in its compactness and degree of cementation, such as hollowing, looseness, etc., there will be a local abnormal area of elastic wave impedance. These wave impedance difference interfaces, as well as the elastic wave impedance abnormal area caused by material inhomogeneity, are all scattering sources. The scattering source will generate scattered waves under the excitation of shock waves. The greater the difference in elastic wave impedance, the stronger the energy of the scattered wave, as shown in Fig. 5.

![Schematic diagram of coherent frequency method](image)

According to the observed scattered wave field, the image of the scattering source inside the structure can be reconstructed, so as to understand the position and degree of difference of anomalous objects. When the area of the abnormal body is large, multiple reflections will be formed between the surface and the abnormal body. The period of the multiple wave is the ratio of the two-way path to the wave velocity, and the reciprocal of the frequency period of the multiple wave is the ratio of the wave velocity to the two-way path [19]. Through the frequency spectrum analysis of the vibration record, the frequency with a larger amplitude is found, and several possible anomalous body interfaces are determined, as shown in Fig 6.

![Depth and amplitude relationship diagram](image)
According to the excellent frequency, the depth of the corresponding interface can be calculated, and the size of the spectrum value corresponds to the product of the interface scale and the degree of difference. Frequency and depth conversion formula (1) and (2):

\[ S = \frac{v}{2f} \]  
\[ A(S) = A(f) \]

Where \( S \) is the depth, \( v \) is the wave speed, and \( f \) is the frequency.

### 3.2. Spectrum imaging technology

When detecting the aqueduct, due to the short propagation distance and long wavelength of the scattered wave, the imaging technique using the in-phase superposition method of the scattered wave is not effective, and a new processing method—acoustic wave scattering coherent frequency imaging is needed, as shown in Fig. 7. First, the received reflection time domain record is converted to the frequency domain through fast Fourier transform. Then according to the conversion formula of frequency and depth, the frequency domain record is converted into the spatial domain depth record with the concrete wave speed. Connect the data obtained from the point-by-point test on the survey line into a profile to form a profile of the coherent frequency method, and assign the frequency spectrum value to each depth point for imaging display, as shown in Fig. 8. Profile image color display settings: Set the maximum value to 1 through normalization, segment the amplitude setting threshold, and assign appropriate color codes to paragraphs with different amplitudes. The color code can be divided into 4 levels to highlight the larger amplitude. And divide the amplitude, select the larger value range, divide it into 2 grades, and use eye-catching colors. For smaller amplitudes, set the background color. This color processing is relatively simple, but the visual effect is excellent, clear and intuitive.

![Fig.7 Schematic diagram of coherent frequency method calculation](image)

![Fig.8 The display mode of the frequency spectrum corresponding to the interface depth](image)
that the scattering in the area is weak. The medium is uniform. The X-axis of the image represents the horizontal position of the detection, and the Y-axis represents the depth. The positions of red, yellow, green, and blue in the figure indicate the spatial distribution of different intensity scattering sources. Internal defects of concrete: the hollow, segregated and loose areas are the strong scattering interface, which is the red area. The detection points can be arranged along the survey line or grid to form a detection profile or 3D image.

The basic principle of identification is similar to that of geological radar:

1) The first interface with strong red reflection from light to dark, generally the bottom interface of the structure;
2) Strong reflection above the bottom interface, generally a defect;

![Image](image.png)

**Fig.9** Coherent frequency method results of typical profile

4. Model test and engineering application practice

4.1. Defect model test verification

In order to verify the feasibility of robot detection, concrete model tests were carried out. The model is rock-fill concrete, and the size of model is shown in Fig.10. Defects are preset as follows: 1) Sprinkle a layer of 2-3cm thick stone powder and second pouring at a depth of 70cm from the surface to simulate cracks; 2) Partially filled with 10cm thick foam to simulate hollowing defects; 3) Partially filled with large-diameter blocks to simulate uneven distribution of concrete. The robot reciprocates vertically and horizontally on its upper surface, and the typical results are shown in Fig.11.

![Image](image.png)

**Fig.10** Model diagram
Continuous red stripes indicate that there is a continuous strong reflection interface, and the local red stripes indicate that there is a small local strong reflection interface. It can be seen from the figure that the two construction joints at a depth of 70cm show strong red reflection, the interface is clear and obvious, the interface of the 140cm bottom plate is obviously accurate, and there is strong red reflection locally above the bottom interface, indicating that the concrete is locally uneven.

4.2. Engineering applications

The field test of concrete aqueduct nondestructive testing robot was carried out on October 24, 2020. The test was conducted in the section 2 of shahenan-huanghenan of Zhengzhou, the main canal of the south to North Water Diversion Project. The total length of the aqueduct is about 120m, and the section structure is shown in Fig. 12.
The aqueduct concrete non-destructive testing robot was used for testing on site, and the results are shown in Fig. 14, Fig.15.

From the test results, the bottom interface of concrete at 50cm is very clear. There are basically no other reflective interfaces in the area above the bottom interface, which indicates that the concrete of the Shuiquangou aqueduct floor is uniform, dense and complete, and no defects such as voids have been found.

5. Conclusions
In view of the characteristics of the South-to-North Water Diversion Project, the use of coherent frequency imaging technology based on the scattering principle, the selection of high-precision and high-sensitivity sensors and collectors, the aqueduct concrete non-destructive inspection robots is integrated and assembled. Based on a robot walking platform with wireless communication, the device completes the automatic excitation, collection and imaging of elastic waves, so as to realize the rapid
detection of the uniformity and compactness of the concrete structure of the aqueduct. Through the field test and demonstration application of the aqueduct concrete inspection robot inspection equipment, it is verified that the data collection ability of the inspection robot meets the design index, and the inspection efficiency is increased by more than 50%. According to the test situation, the follow-up improvement plan of the system hardware should strengthen the maneuverability of the car, realize precise positioning, strengthen the energy of the seismic source, and improve the overall reliability of the system.

Acknowledgment
We gratefully acknowledge the invaluable contribution of YANG Bo, SHANG Feng and JIANG Hui during this collaboration. This work was financially supported by the National key research and development plan "Efficient development and utilization of water resources" of PRC (2018YFC0406901).

References
[1] Feng Zhiming, Yang Yanzhao, You Zhen. Research on the Water Resources Restriction on Population Distribution in China[J]. Journal of Natural Resources, 2014, 29(10): 1637-1648.
[2] Wang Xi, Wang Zhan, Yang Wentao, Xi Xuejuan, et al. Shortage of water resources in China and countermeasures[J]. Environmental Engineering, 2014, 32(07): 1-5.
[3] Long Qiubo, Jia Shaoqiang, Wang Dangxian. Disparity in China’s water use statistics[J]. Resources Science, 2016, 38(02): 248-254.
[4] Li Y Y, Cao J T, Shen F X, et al. The changes of renewable water resources in China during 1956-2010. Science China: Earth Sciences, 44(09): 2030-2038.
[5] Liu Jing, Bao Zhenxin, Liu Cuishan. Change law and cause analysis of water resources and water consumption in China in past 20 years[J]. Hydro-Science and Engineering, 2019(04): 31-41.
[6] Cheng Dehu, Su Xia. Technical advancement and demand of Middle Route Scheme of South-to-North Water Diversion Project[J]. China Water Resources, 2018, (10): 24-27.
[7] Wang Lunwen, He Junrong, You Ling, et al. Processing design of the Karst of Dali I Section of the Central Yunnan Water Diversion Project in Jifu Village[J]. Water Resources Planning and Design, 2019, (12): 1-9.
[8] XU Jiang, XUANG Guoxin, LUO Daiming, et al. The application of high pier and long-span continuous rigid frame aqueduct technology in Guizhou Canyon Mountain[J]. Pearl River, 2016, 37 (2): 8-15.
[9] LIU Xiaopeng, LYU Bin. Analysis and Repair for Cracks in Aqueducts of a Water Conveyance Project in Xinjiang[J]. Yellow River, 2018, 40 (1): 123-126.
[10] LI Jinyu, CAO Jianguo. Research and application of durability of hydraulic concrete[J]. Beijing: China power press, 2004.
[11] CHEN Gaixin. Application and development tendency of concrete durability research[J]. Journal of China Institute of Water Resources and Hydropower Research, 2009, 7(2): 280-285.
[12] GU Peijing, WANG Lanlan, DENG Chang, et al. Review of typical failure characteristics of aqueduct structures in China[J]. Advances in Science and Technology of Water Resources, 2017, 37(5): 1-8.
[13] JIANG Haiying. Genesis Analysis And Disposal Measures Of Cracks In Flume Body Of Kizi River Aqueduct[J]. Water Resources Planning and Design, 2019, (4): 114-117.
[14] CHEN Guoxi. Cause analysis and treatment method of diseases in Xi’an Heihe Aqueduct Project[D]. Chang’an University, 2016.
[15] SHANG Feng, ZHU Yanzhi, JIU Yongzhi. Safety evaluation and disease treatment of reinforced concrete aqueduct in service[J]. Water Resources and Hydropower Engineering, 2018, 49(12): 208-214.
[16] SUN Zhiheng, LU Yihui, YUE Yuezheng. The detection, evaluation and defect repair engineering application of hydraulic concrete building[M]. Beijing: China water resources and Hydropower Press, 2004.
[17] ZHAO Xiaopeng, JIANG Hui, ZHAO Yonggui. The application of acoustic scattering imaging technology in quality inspection of wind power tower foundation concrete[J]. Nondestructive Testing, 2020, 42(06):7-11.

[18] ZHAO Xiaopeng, JIANG Hui, ZHAO Yonggui. Application of Seismic Scattering Technique to Prospecting of Boulders in Submarine Tunnel: a Case Study of Hengqin Tunnel[J]. Tunnel Construction, 2019, 39(S2): 352 -357.

[19] LYU Xiaobin, WU Jiaye. Theory and application of shock elastic wave[M]. Beijing: China water resources and Hydropower Press, 2016.