

Review

Review of Research Progress on Acoustic Test Equipment for Hydrate-Bearing Sediments

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Abstract: When acoustic waves propagate through hydrate samples, they carry extensive information related to their physical and mechanical properties. These details are comprehensively reflected in acoustic parameters such as velocity, attenuation coefficient, waveform, frequency, spectrum, and amplitude variations. Based on these parameters, it is possible to invert the physical and mechanical indicators and microstructural characteristics of hydrate samples, thereby addressing a series of issues in hydrate development engineering. This study first provides an overview of the current applications and prospects of acoustic testing in hydrate development. Subsequently, it systematically elaborates on the progress in research on acoustic testing systems for hydrate samples, including the principles of acoustic testing, ship-borne hydrate core acoustic detection systems, laboratory hydrate sample acoustic testing systems, and resonance column experimental systems. Based on this foundation, this study further discusses the development trends and challenges of acoustic testing equipment for hydrate-bearing sediments.

Keywords: hydrate; acoustic; test systems; column



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1. Introduction

Natural gas hydrates are crystalline substances formed by the combination of natural gas and water under high-pressure and low-temperature conditions [1,2]. Due to their ice-like appearance and flammability upon exposure to heat, they are also known as “flammable ice”. Natural gas hydrates are widely distributed in nature, being primarily found in permafrost regions (<10%) and continental margin basins (≥90%). The total methane reserves in natural gas hydrates [3] are estimated to be approximately $2 \times 10^{16} \text{ m}^3$, which is twice the total carbon stored in traditional fossil fuels (coal, oil, natural gas, etc.) [4]. It is estimated that globally recoverable hydrate resources could meet human energy needs for the next 200 years [5–7], highlighting their significant potential in alleviating the energy crisis and improving air quality [8,9].

However, achieving the long-term and large-scale commercial exploitation of natural gas hydrates still faces numerous challenges, including reservoir heterogeneity, immature exploration and development technologies, and potential geological engineering risks [10–12], all of which hinder the safe development of hydrate resources. Among these challenges, geological engineering risks primarily include issues such as sand production [13–15], reservoir instability [16], submarine landslides [17,18], methane leakage [19], and slope instability [1,20]. In terrestrial areas, the environmental problems associated with geohazards caused by the dissociation of hydrates should likewise not be ignored [21–23]. Clarifying the quantitative relationship between hydrate properties and geological engineering risks is crucial. The early exploration of the physical and mechanical properties of hydrates relied on geophysical observations and in situ overpressure coring tests due to technological and equipment limitations [24–28]. With the development of experimental

laboratory techniques and equipment, many researchers have shifted their focus to indoor experiments [29]. Establishing indoor simulation devices for hydrate property testing and conducting large-scale indoor experiments have accelerated the exploration of the physical and mechanical properties of hydrates, thereby promoting the evolution of commercial hydrate development [29].

Acoustic testing, as a fast, non-destructive, and convenient method, possesses unique advantages in hydrate property testing. When acoustic waves interact with hydrate-bearing sediment, information related to the physical and mechanical parameters and microstructural changes in the medium is carried in the received waves. Consequently, acoustic testing is increasingly utilized in both laboratory and field experiments involving hydrates [30–32]. However, hydrate-bearing sediments require strict temperature and pressure conditions for their stable existence [33–35], making it challenging to directly use conventional experimental systems for sediment property measurements. As a result, numerous research institutes have embarked on the development of acoustic experimental systems for hydrate-bearing sediments, laying the foundation for studying their physical and mechanical behaviors.

The purpose of this study is to comprehensively summarize the current application status of acoustic testing systems for hydrate-bearing sediments, explore the prospects of these systems in the field, and enhance their application. We first summarize, analyze, and evaluate the current research progress on acoustic testing systems for hydrate-bearing samples and identify the deficiencies of current acoustic testing equipment. Based on these analyses, the development trends, challenges, and future prospects of acoustic testing equipment for hydrate-bearing samples are discussed and forecasted.

2. Application Status and Prospects of Acoustic Testing in Hydrate Development

When acoustic waves propagate through sediment, they carry abundant information related to the physical and mechanical properties of the sediment. By analyzing dynamic indicators of the acoustic waves such as intensity (amplitude), attenuation, and kinematic features like velocity and phase changes, it is possible to invert the physical and mechanical indicators and microstructural characteristics of hydrate sediments. The application status and prospects of acoustic testing in hydrate development include the following:

- (1) Evaluation of hydrate development strata integrity and wellbore stability (determination of the reservoir state through changes in acoustic signals);
- (2) Geological stratification and saturation determination of hydrate reservoirs;
- (3) Seismic response analysis and bottom simulating reflector (BSR) identification (identification of BSR through the difference in wave velocity between hydrates and free gas layers);
- (4) Calculation of the dynamic Young modulus, shear modulus, and Poisson's ratio of hydrate samples;
- (5) Establishment of correlations between the acoustic parameters of hydrate samples and geotechnical parameters using correlation analysis;
- (6) Identification of the fractures and characterization of anisotropy in hydrate reservoirs;
- (7) Description of the internal crack development and evolution laws under loading conditions in hydrate samples;
- (8) Study of the damage evolution equations and constitutive relationships under the uniaxial, triaxial, and creep tests of hydrate samples;
- (9) Analysis of porous medium fluid flow effects in hydrate reservoirs;
- (10) Inversion of the physical parameters of hydrate reservoirs such as porosity, density, pressure, temperature, and fracture.

3. Research Progress of Hydrate Acoustic Testing Systems

Hydrate acoustic testing systems offer significant advantages and are widely applied in both laboratory and field settings. These systems are categorized as follows based on the frequency of the acoustic waves used: bend element testing systems (high-frequency

sound waves of 0.02~1 MHz) and resonance column testing systems (low-frequency sound waves of 10~1000 kHz).

3.1. Bend Element Testing Systems

Bend element testing systems are characterized by their simple structure and low cost, making them the most commonly used experimental equipment in laboratories for measuring the velocity of hydrate samples [36]. The core of the bend element testing system is the bending element, which is made from piezoelectric ceramic bilayers. When one end of the bilayers receives an excitation voltage, the entire element bends due to the piezoelectric effect, emitting a sound signal (Figure 1a). Conversely, when the piezoelectric element undergoes forced bending deformation, it generates a voltage due to the inverse piezoelectric effect, allowing the reception of electrical signals (Figure 1b).

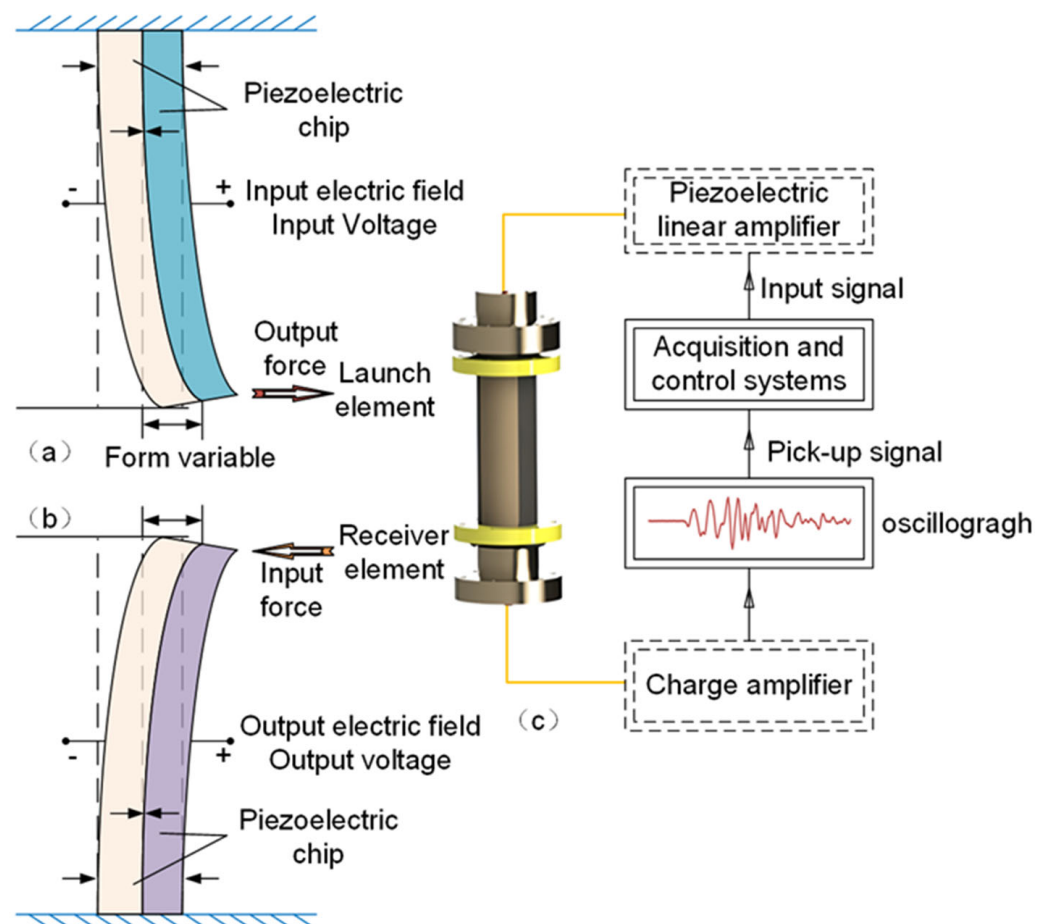


Figure 1. The bend element testing system: (a) the working principle of the launching bending element; (b) the working principle of the receiving bending element; (c) the bending element shear wave velocity test system (modified from [37]).

Utilizing this bending element characteristic, the bend element system consists of two separate piezoelectric ceramic bending elements placed at both ends of a hydrate sample, with one serving as the transmitting element and the other as the receiving element. When an electrical signal is applied at one end (the top or bottom of the sample), the bending element deforms and emits a signal, perturbing the sediment in wave form. This disturbance propagates through the sediment and is captured by the receiving element at the opposite end, converting it back into an electrical signal, thereby completing the sediment velocity measurement experiment. Both bending elements are connected to signal amplifiers to ensure clear signal recording during signal input and output. Data acquisition

and control devices manage signal emission, reception, and experiment information storage and recording (Figure 1c). Bend element testing systems are widely used for on-site acoustic measurements of pressure core samples and indoor experimental research.

3.1.1. Shipboard Hydrate Core Acoustic Detection Systems

Research groups in Europe, America, and Japan are pioneers in the study of shipboard hydrate pressure core detection technology, establishing multiple integrated detection systems and corresponding analytical methods for hydrate pressure core samples. These advancements include the MALLIK Mobile Core Laboratory designed by Anadarko Petroleum Corporation [38]. Independently developed by the Georgia Institute of Technology, the Instrumented Pressure Testing Chamber (IPTC) [39] and PCUTS [40] not only integrate acoustic detection modules but also incorporate resistivity testing modules. However, due to structural limitations, these devices cannot provide axial loading capability to the specimen. This also means that they cannot carry out triaxial mechanical experiments. Figure 2 illustrates the physical connection between PCUTS and pressure core retrieval equipment.

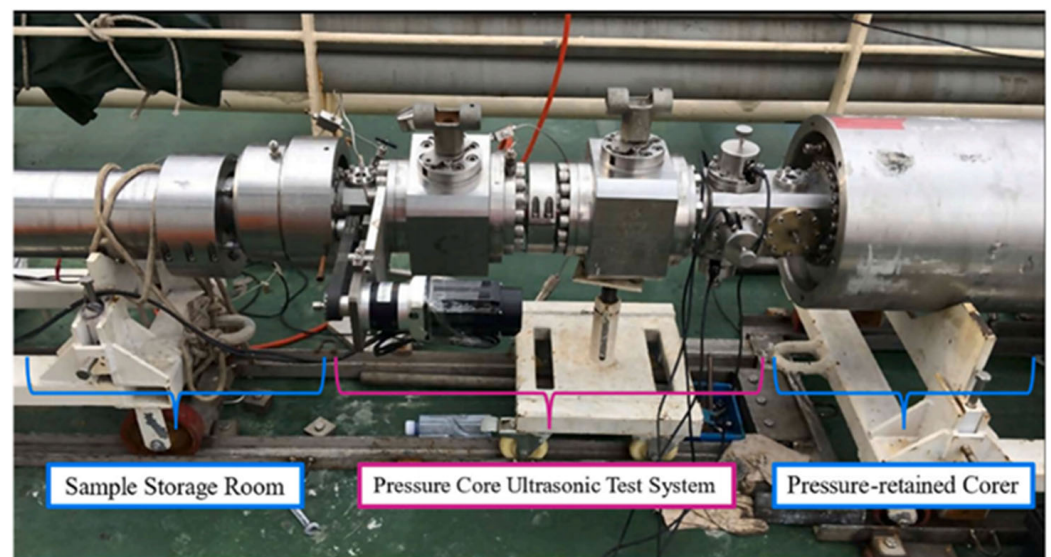


Figure 2. A picture of the combined Pressure Core Ultrasonic Test System (PCUTS) and pressure-retained corer [40] device.

Subsequently, the Pressure Core Analysis and Transfer System (PCATS), developed by Geotek Ltd. in the Daventry, UK, was designed to facilitate the transfer of cores under pressure conditions. PCATS features a triaxial configuration that allows in situ acoustic and large-strain rock mechanics testing, as well as the direct measurement of permeability [41]. Details of the sample transfer and testing methodologies can be found in the references [42,43]. Building upon PCATS, the Pressure-core On-board Transfer and Analysis System (POTAS) was jointly developed by the Dalian University of Technology and Zhejiang University (Figure 3) [44]. This system utilizes acoustic transducers with a self-coupled curved end-face design, adjustable based on the curvature facing the diameter of hydrate-bearing cores to accommodate various sample sizes. POTAS also includes a reserved connection port for CT scanning units. The open internal threaded connection end can be directly sealed onto the CT scanning unit, meeting the integrated detection requirements of CT scanning and ultrasonic testing.

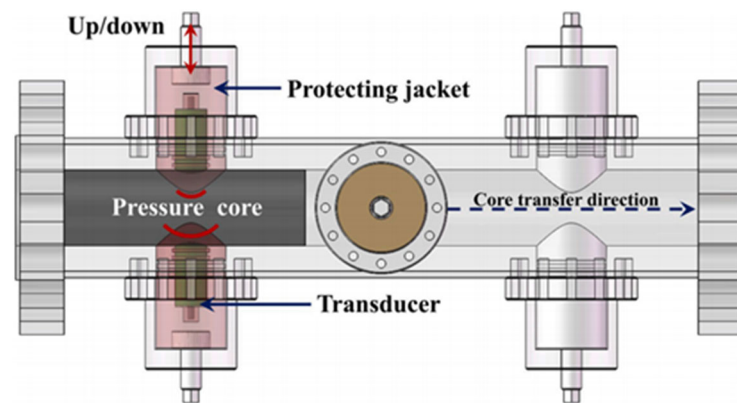


Figure 3. A structural diagram of the combined device of the Pressure-core On-board Transfer and Analysis System (POTAS) [44].

3.1.2. Laboratory Hydrate Sample Acoustic Testing Systems

Based on the foundation of the bending element test system, various research institutions have successively developed multiple indoor acoustic testing systems suitable for hydrate-bearing samples. These indoor hydrate sample acoustic testing systems primarily consist of five components: a gas injection system, reaction vessel, temperature control system, gas recovery system, and data acquisition system. The experimental setups can be categorized structurally into one-dimensional, multi-dimensional, and integrated indoor hydrate sample acoustic testing systems.

- One-dimensional indoor hydrate sample acoustic testing systems

The National Institute of Advanced Industrial Science and Technology (AIST) in the United States developed an indoor hydrate sample acoustic testing system [45], as depicted in Figure 4. This device includes insulation layers, a circulating saltwater bath, a confining pressure fluid layer, and the sample itself, capable of withstanding pressures of up to 25 MPa. The sediment sample is centrally located within the apparatus, enclosed in a rubber barrel, with piezoelectric ceramic sensors positioned at both ends. This setup enables acoustic measurements on $\Phi 50 \times 160 \text{ mm}^2$ hydrate samples during their in situ synthesis and decomposition processes. Similar acoustic testing systems have also been developed by the Dalian University of Technology [46] and the Indian Institute of Technology [47].

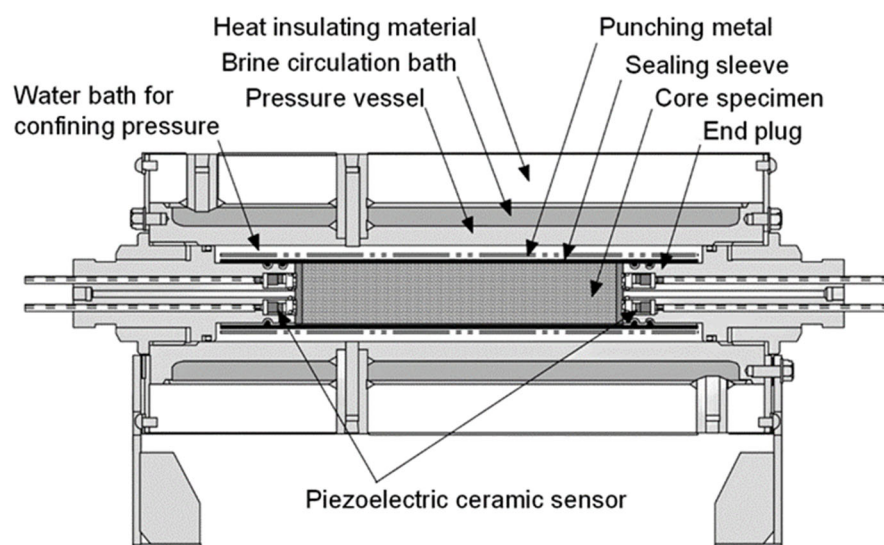


Figure 4. The ultrasonic velocity measurement test set of the Methane Hydrate Research Laboratory, the National Institute of Advanced Industrial Science and Technology (AIST) [45].

In conventional one-dimensional indoor hydrate sample acoustic testing systems, acoustic transducers are typically positioned at both ends of the sample, and these positions are fixed. However, to accommodate samples of different lengths, a clamping device can be installed at both ends of the sample to adjust the distance between the acoustic transducers [48–50]. Simultaneously, the clamping device can compact the sample and apply initial axial stress, ensuring close contact between the acoustic transducers and the sediment, thereby improving the quality of acoustic measurements. This clamping device structure (Figure 5) allows for clamping at one end or both ends [51,52].

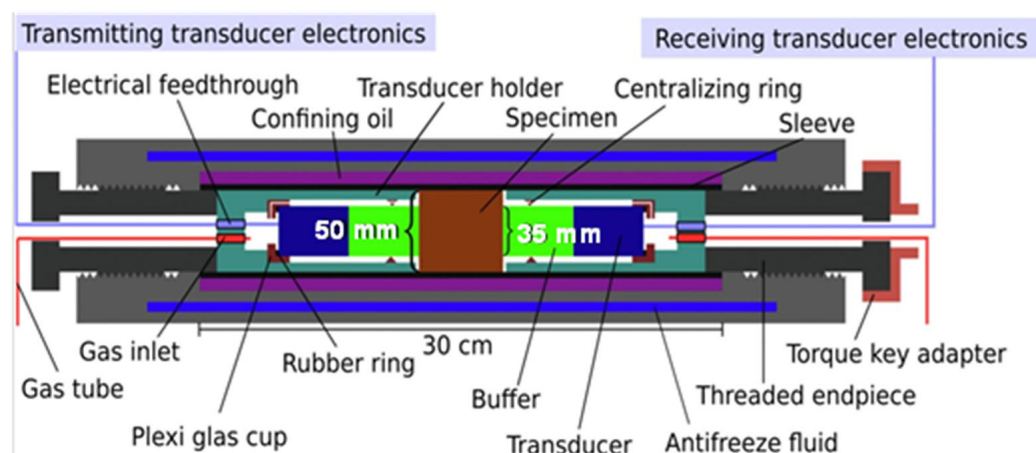


Figure 5. A schematic diagram of the locking structure at both ends [51,52].

- Multi-dimensional Indoor Hydrate Sample Acoustic Testing Systems

In the realm of indoor hydrate sample acoustic testing systems, the conventional setups are typically limited to capturing one-dimensional acoustic parameters due to structural constraints. However, in the processes of hydrate formation and decomposition, it becomes crucial to ascertain specific details such as the location and extent of decomposition, which are difficult to achieve solely based on one-dimensional acoustic parameters. To address this challenge, the China University of Petroleum has developed a multi-dimensional indoor hydrate sample acoustic testing system where the hydrate reaction vessel is equipped with three sets of opposing acoustic probes, enabling separate measurements of hydrate wave velocities at different layers [53,54]. Taking this concept further, the Qingdao Institute of Marine Geology [55] has pioneered a two-dimensional imaging indoor hydrate sample acoustic testing system, as illustrated in Figure 6. This device incorporates four pairs of piezoelectric ceramic sensors, each transmitting and receiving signals using cross-transmission methods (where signals transmitted by each probe can be simultaneously received by 4 sensor probes, resulting in 16 waveform files per measurement). Finally, through tomographic imaging techniques, the acoustic data are processed to generate two-dimensional acoustic profiles within the sediment, facilitating a comprehensive “3D” mesh analysis of hydrate variations during the formation and decomposition processes.

Currently, established acoustic measurement devices effectively characterize the overall geophysical properties of hydrate-bearing sediment samples. However, there are still shortcomings in describing local and microscopic variations. Even with the application of two-dimensional acoustic imaging technology, the characterization accuracy remains noticeably low. Therefore, the development of more advanced acoustic tomography imaging technology is crucial for future research on defect localization and microscopic evolution within hydrate-bearing sediment samples.

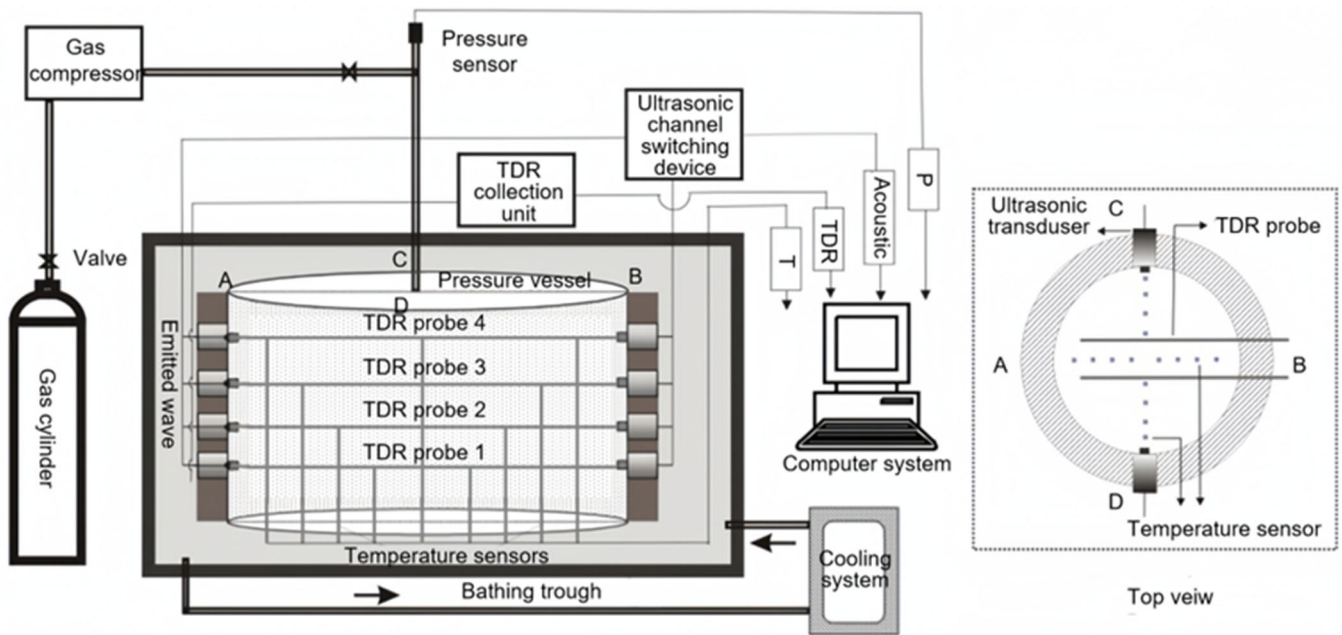


Figure 6. The acoustic measurement system of the Qingdao Institute of Marine Geology (QIMG) for the two-dimensional imaging of hydrate cores [55].

- Hydrate Sample Combined Acoustic Detection System

To obtain more comprehensive physical parameters of hydrate samples, various research institutions have integrated multiple measurement techniques into indoor hydrate sample acoustic detection systems. Researchers such as Hu Gaowei and Ye Yuguang [56–60] from the Qingdao Institute of Marine Geology, China Geological Survey, have integrated time-domain reflectometry (TDR) into indoor acoustic testing systems for investigating the geophysical properties of hydrate-bearing samples (Figure 7). In the experimental setup, a pair of piezoelectric ceramic sensors are placed at both ends of the $\Phi 68 \times 150 \text{ mm}^2$ hydrate sample within the main reaction vessel to monitor acoustic behavior. The TDR measurement system consists of a TDR detector and two TDR probes. One TDR probe is a metal ring embedded in a slot on the inner wall of a polytetrafluoroethylene cylinder, while the other is a metal cylinder inserted into the center of the sample. The TDR measurement system identifies changes in characteristic impedance within the sediment and calculates hydrate saturation using empirical formulas. The introduction of the TDR measurement system enhances the accuracy of hydrate saturation identification, thereby establishing a more precise correlation between hydrate saturation and its acoustic properties.

Similarly, to enhance the accuracy of saturation identification, institutions such as the China University of Petroleum (East China) [61], Peking University [62], and Chengdu University of Technology [63] have integrated resistivity testing modules into indoor hydrate sample acoustic testing systems.

The Qingdao Institute of Marine Geology, China Geological Survey [64,65], has developed an acoustic-triaxial integrated testing system, as shown in Figure 8. In addition to basic acoustic testing, this system includes an axial load application device, allowing acoustic measurements under triaxial stress conditions for $\Phi 39 \times 120 \text{ mm}^2$ samples and synchronized acoustic measurements during creep loading stages. This approach closely simulates actual reservoir conditions and operational scenarios during development.

The U.S. Geological Survey Woods Hole Science Center [66,67] has integrated multiple testing modules into an indoor hydrate sample acoustic testing system and developed a comprehensive hydrate sample testing apparatus, as depicted in Figure 9, which includes temperature testing modules, resistivity testing modules, and more. These advancements provide a more comprehensive characterization of the physical properties of hydrate samples.

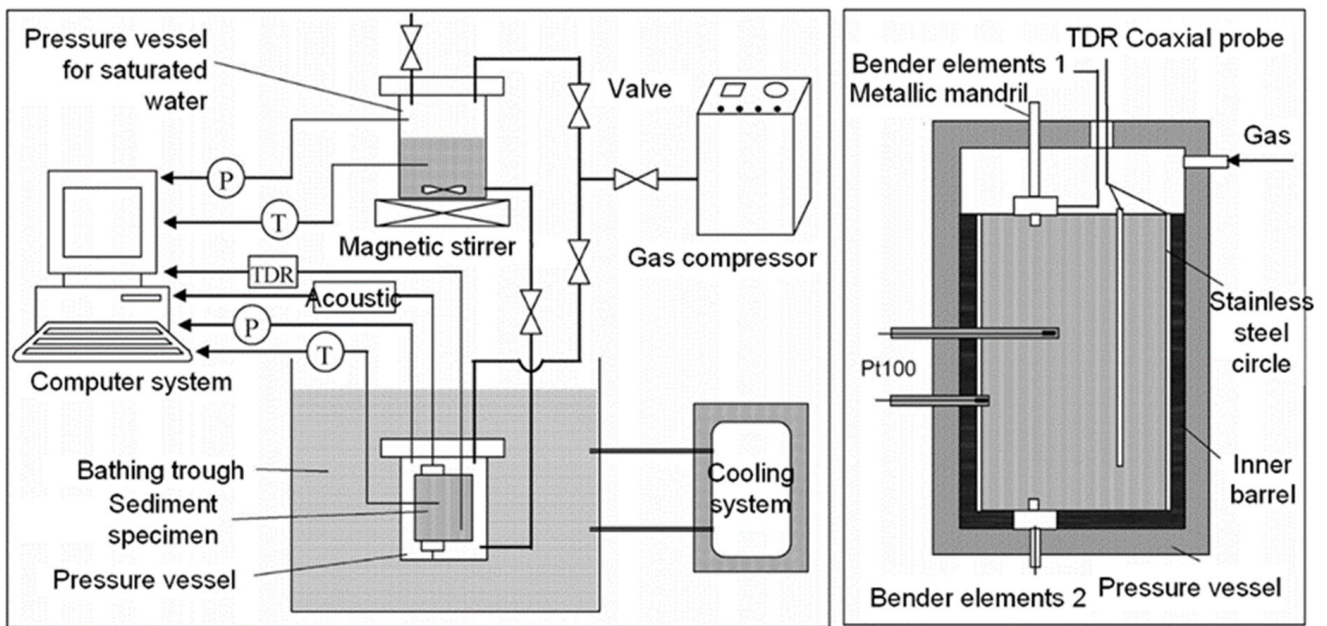


Figure 7. The experimental apparatus of the Qingdao Institute of Marine Geology (QIMG) for geophysical research on gas hydrate-bearing sediments [56].

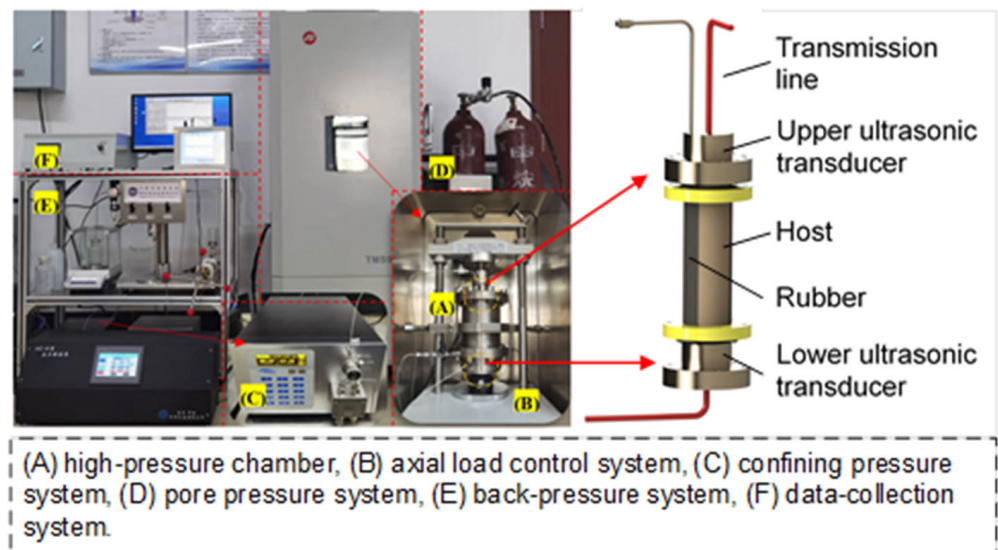


Figure 8. The triaxial-acoustic joint testing system of the Qingdao Institute of Marine Geology (QIMG) for hydrate-bearing sediments [64,65].

The above hydrate sample combined acoustic detection system is still considered as a black box experimental system, where it is not possible to directly observe fine changes in hydrate samples during research. Therefore, the Qingdao Institute of Marine Geology [68–70] integrated X-ray CT with an acoustic measurement system to establish a joint hydrate CT–acoustic testing system for hydrate-bearing sediments (Figure 10). The sample chamber is made of PEEK material, which facilitates X-ray penetration and improves the imaging quality. Based on this system, experiments related to microscopic structural changes in hydrates can be conducted, enhancing the understanding of internal microstructural changes in hydrate samples.

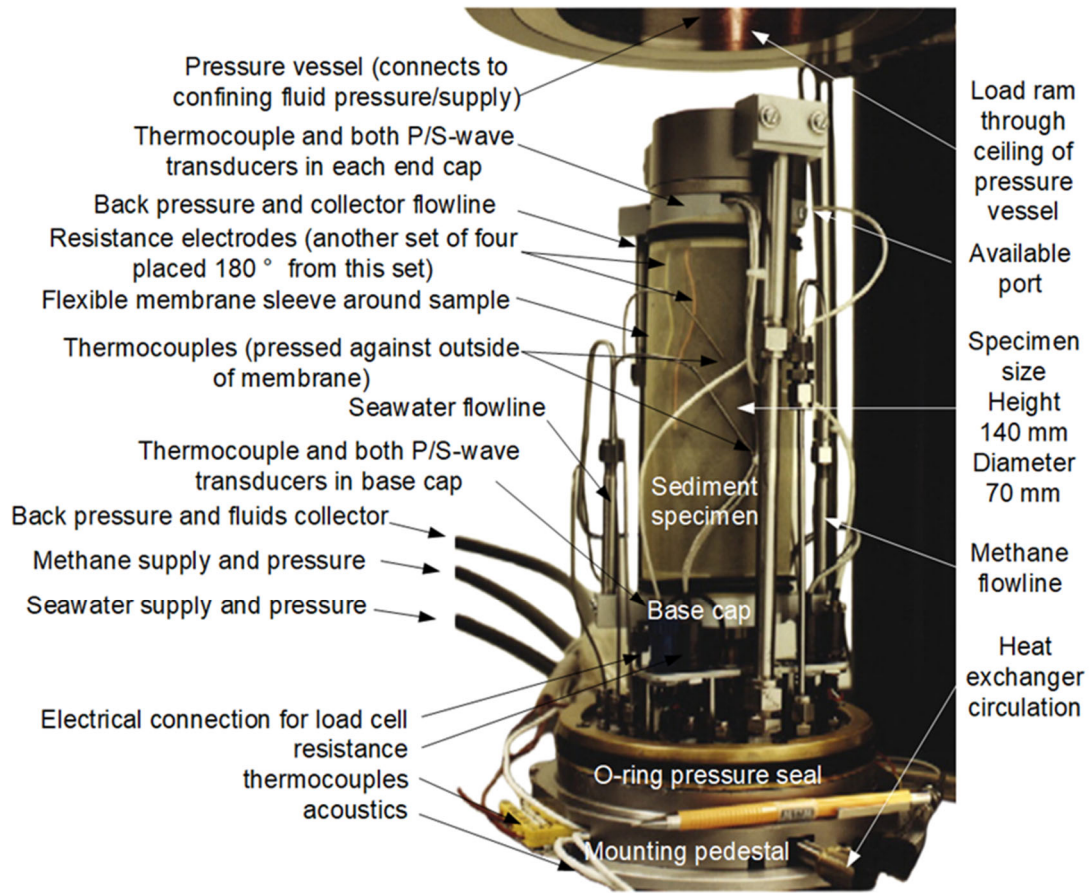


Figure 9. The experimental apparatus of the U.S. Geological Survey Woods Hole Science Center for geophysical research on hydrate-bearing sediments [67].

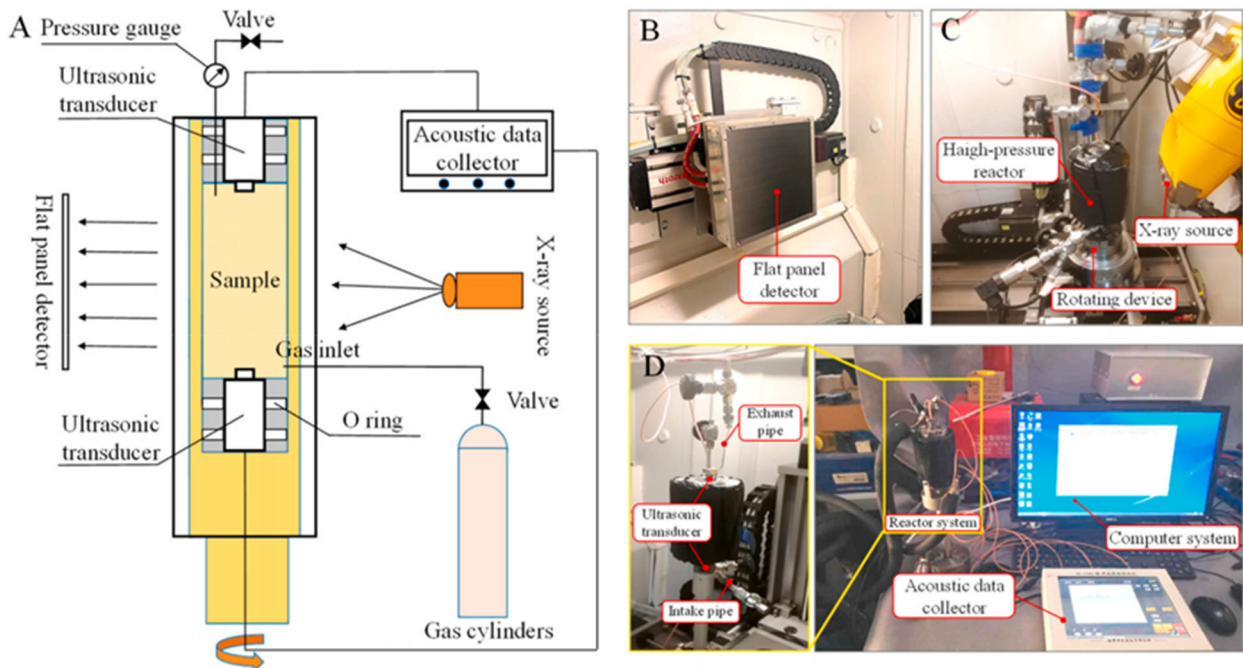


Figure 10. The CT-acoustic joint testing system of the Qingdao Institute of Marine Geology (QIMG) for hydrate-bearing sediments [68–70]: (A) system schematic diagram; (B) X-ray flat panel detector; (C) X-ray source; (D) ultrasonic detection apparatus and high-pressure reactor.

3.2. Resonant Column Experiment System

Resonant column testing allows for the measurement of the acoustic parameters of hydrate-bearing samples at close to seismic frequencies (<500 Hz), making it highly relevant for interpreting field data [71,72]. This testing method is based on the principle of resonance [73]. When sediment is subjected to periodic external forces, resonance occurs if the frequency of the external force matches or is close to the natural frequency of the sediment. At resonance, the sediment reaches maximum amplitude, maximizing energy transfer efficiency [74,75]. By monitoring the vibration frequency and amplitude of the sediment, the acoustic properties of the sediment can be obtained [76,77].

The University of Southampton modified an unfixed Stokoe-type resonant column apparatus [78] to meet the testing requirements of hydrate-bearing samples. They incorporated a specialized resonant column testing system for the acoustic measurements of hydrate samples, adding features such as a low-temperature coolant and a high-pressure chamber [79–82], as shown in Figure 11. This setup enables acoustic resonance testing of $\Phi 70 \times 140 \text{ mm}^2$ samples. During acoustic measurements, an electromagnetic field is induced by applying voltage to the driving coil, causing the magnet to rotate or move linearly, thereby driving the connected mechanism to generate torsional or bending vibrations in the sediment. Subsequently, the frequency and amplitude of the applied voltage are adjusted stepwise to match the resonance frequency of the sample and its attached driving mechanism. Based on the resonance frequencies and wave attenuation characteristics of the bending and torsional vibrations, the acoustic properties of the sediment are calculated [80].

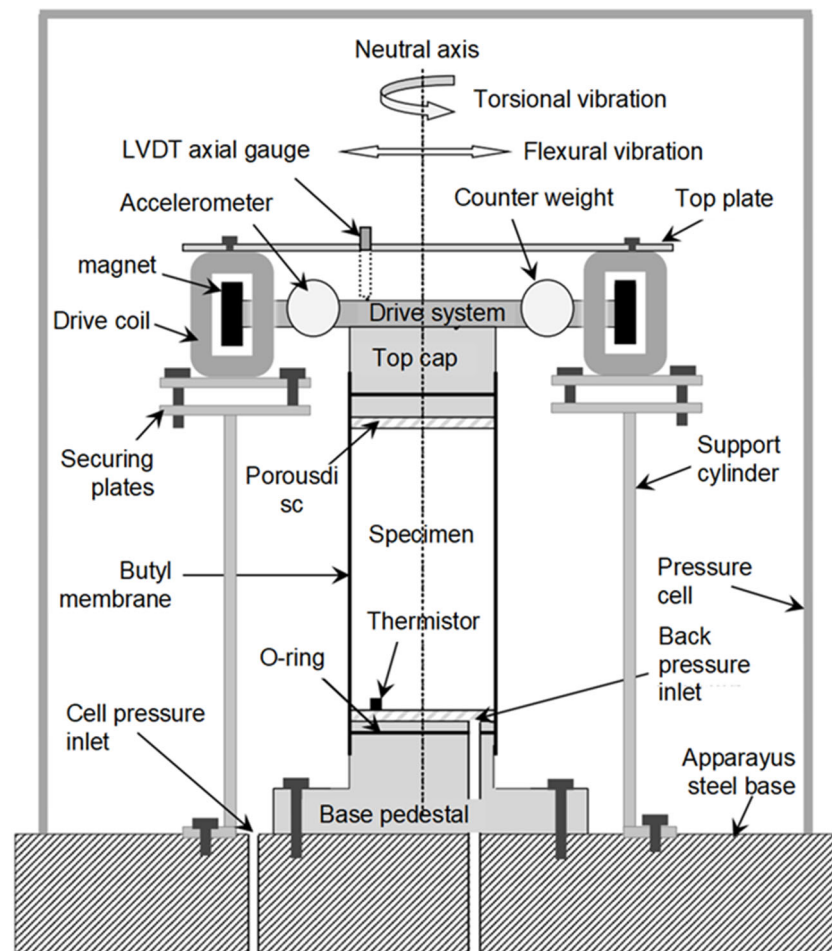


Figure 11. The resonant column measurement system of the University of Southampton for hydrate-bearing sediments [83].

Researchers from the University of Waterloo in Canada [80] and the Qingdao Institute of Marine Geology [84] (Figure 12) have similarly developed and designed acoustic measurement devices for hydrate-bearing sediments based on resonance column testing systems. The principles and structures of these devices are largely similar to those of the aforementioned systems. These instruments play a crucial role in exploring the geophysical properties of hydrate-bearing sediment samples.

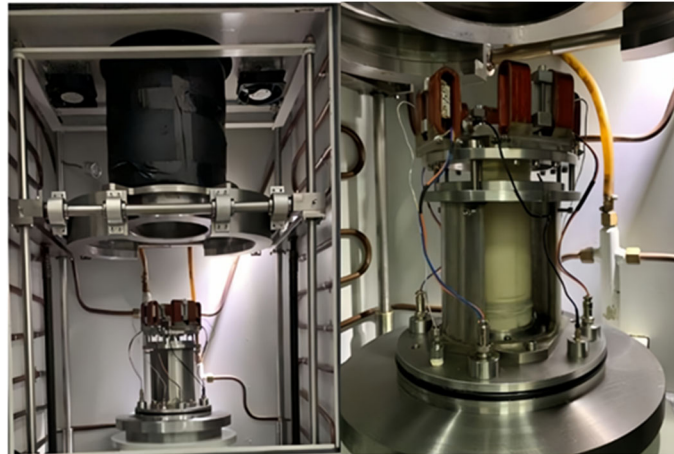


Figure 12. The resonant column measurement system of the Qingdao Institute of Marine Geology (QIMG) for hydrate-bearing sediments [84].

Currently, the application uses the above equipment to obtain a complete sonic curve, through which sediment wave velocity, wave impedance, and elasticity parameters can be calculated to characterize the stratigraphic properties [85]. The difference in wave velocity can also be used to recognize BSR and determine whether there is hydrate endowment [86]. Through the continuous wave velocity curve, the formation state can be detected [87].

4. Conclusions and Outlook

Acoustic testing, as a rapid, non-destructive, and straightforward detection method, extracts acoustic parameters to reflect the physical and mechanical properties of hydrate-bearing sediment samples. This paper systematically summarizes the progress made in the research on hydrate acoustic testing devices and draws the following conclusions:

- (1) Acoustic testing is a non-destructive method that can be widely applied in various fields of hydrate testing. It indirectly extracts the physical and mechanical properties of hydrate-bearing sediment samples and holds promising development prospects.
- (2) Currently, established acoustic measurement devices effectively characterize the overall geophysical properties of hydrate samples. However, there is still a lack of description regarding local and microscopic variations. Even with the application of two-dimensional acoustic imaging technology, the characterization accuracy remains notably low. Therefore, developing higher-level acoustic tomography imaging technology is crucial for accurately locating internal defects and studying the microscopic evolution of hydrate samples in the future.
- (3) Feasibility studies of four-dimensional ultrasonic testing are recommended. Establishing a four-dimensional ultrasonic testing system to extract parameters such as velocity, travel time, amplitude, AVO (amplitude versus offset) response, impedance, and reflectivity can provide higher-level monitoring and analysis of fluid movement patterns, pressure, and temperature changes during hydrate formation or decomposition. This approach allows for a more systematic and detailed analysis of microscopic structural changes.
- (4) The application of acoustic emission technology, as an important branch of acoustic measurement, has rarely been reported for hydrate-bearing samples. This technology

holds great potential for monitoring grain dislocation movement, crack propagation, and evolution within hydrate-bearing samples and has significant practical implications for the future development of hydraulic fracturing for increased production from hydrate resources.

Finally, it is worth mentioning that the purpose of this study is not to compare the gap between the different equipment in the acoustic study of hydrates. Rather, it is to describe the process of equipment development in hydrate acoustic research, ranging from the earliest individual acoustic measurements to the integration of different tools to enrich hydrate acoustic study, demonstrating the process of micro-detail refinement. Finally, we propose directions for the development of hydrate acoustic equipment, including four-dimensional ultrasonic testing and the application of acoustic emission technology, as well as the objective prospects of acoustics for multi-scenario applications in hydrate research. We hope that through this study, we can promote the advancement of hydrate acoustic equipment and research and better serve the safe production of hydrates.

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