

IEEE Guide for the Mechanical Acoustic Imaging Testing of High-Voltage Reactors

IEEE Power and Energy Society

Developed by the
Transmission and Distribution Committee

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of the
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IEEE SA Standards Board

Abstract: Sound is generated by a high-voltage reactor during operation due to vibration with the action of electrical and mechanical stress. Rich state information about the reactor is contained in these sound signals. Therefore, the evaluation of equipment status can be aided by the measurement and research into reactor sound signals. A solid technical foundation for locating abnormal noise in reactors is also provided by the development of acoustic imaging technology. Acoustic imaging technology allows researchers to obtain the distribution of the sound field of a reactor with a microphone array. Combined with knowledge of the reactor structure and operating status, the position of a sound signal and the status of reactors can be effectively determined by researchers with this technology. The characteristics of acoustic imaging technology include noncontact measurement, simple operation, and flexible arrangement. The measured results are important for diagnosing reactor status and identifying sound sources. To guide and provide instructions for the testing of on-site acoustic imaging for reactors, this guide is formulated to specify the test methods, provide the basic requirements, and describe the test instruments, procedures, test data analysis methods, and data records, while providing guidance for the testing of acoustic imaging for reactor.

Keywords: acoustic imaging, high-voltage reactor, IEEE 2824™, microphone array, noncontact measurement, sound signals

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Introduction

This introduction is not part of IEEE Std 2824-2024, IEEE Guide for the Mechanical Acoustic Imaging Testing of High-Voltage Reactors.

This guide is mainly applicable to the testing of acoustic imaging of reactors producing 10 kV and above in operational or testing states. In addition, this method may also be referable transformers, circuit breakers, gas-insulated switchgear, transmission lines, and other power equipment.

In addition, this method may also be referable for online galloping monitoring and other engineering fields, such as vibration measurement of bridges and buildings.

The purpose of this guide is to standardize the basic requirements for the implementation of reactor acoustic imaging measurement and instrument performance, to improve the method for the on-site detection of reactor status, and to improve the efficiency and accuracy of finding the location of abnormal sources of sound caused by defects such as the loosening and discharge of reactors and the associated issues. This guide can assist operation and maintenance personnel with maintenance, and it can improve the technical level of reactor operation status diagnosis.

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IEEE Guide for the Mechanical Acoustic Imaging Testing of High-Voltage Reactors

1. Overview

1.1 Scope

This guide defines test methodologies and technologies for mechanical acoustic imaging. Acoustic fault recognition mechanisms using acoustic imaging technology are described, enabling, for high-voltage reactors, the identification and diagnosis of abnormal radiated noise in a reactor structure caused by mechanical structural abnormalities such as loose structural parts, metal foreign bodies, and loose leads. Additional use cases and test considerations are described to support fault acoustic signal testing of power transformers, switchers, and gas-insulated substations (GIS).

1.2 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

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IEEE Std C37.118.1TM-2011, IEEE Standard for Synchrophasor Measurements for Power Systems.^{8,9}

IEEE Std 111TM-2000, IEEE Standard for Wide-Band (Greater Than 1 Decade) Transformers.

IEEE Std 1615TM-2007, IEEE Recommended Practice for Network Communication in Electric Power Substations.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁰

acoustic chromatogram: A display diagram of the acoustic signal characteristics indicating the intensities of the sound with different colors, taking time as the horizontal axis and frequency as the vertical axis.

acoustic imaging field angle: In the detection of acoustic imaging, the angle formed by the two edges of the largest range where the acoustic image results of the object being tested should be displayed by the test system.

acoustic imaging map: An output result of an acoustic imaging system formed by superimposing a geometric registration on the sound field distribution nephogram with an optical image of the equipment being tested as the background. *See also:* **sound field distribution nephogram**.

array aperture: The maximum linear distance between the geometric centers of any two microphones in a microphone array. *See also:* **microphone array**.

cut-off frequency: The upper and lower limits of the frequency of the sound source that may be accurately located by the imaging system, usually affected by factors such as the frequency response range of the microphone, the number of microphones in the microphone array, and the array aperture. *See also:* **array aperture; microphone array**.

dynamic range of imaging display: The difference between the upper and the lower limits of the sound pressure level display set on the sound field distribution nephogram; used to visually display the sound source position. *See also:* **sound field distribution nephogram**.

imaging angle resolution: The minimum angle is formed by the geometric center of the two sources of sound on the reference emission plane and the center of the array when the bandwidth is 3 dB (see [Figure 1](#)).

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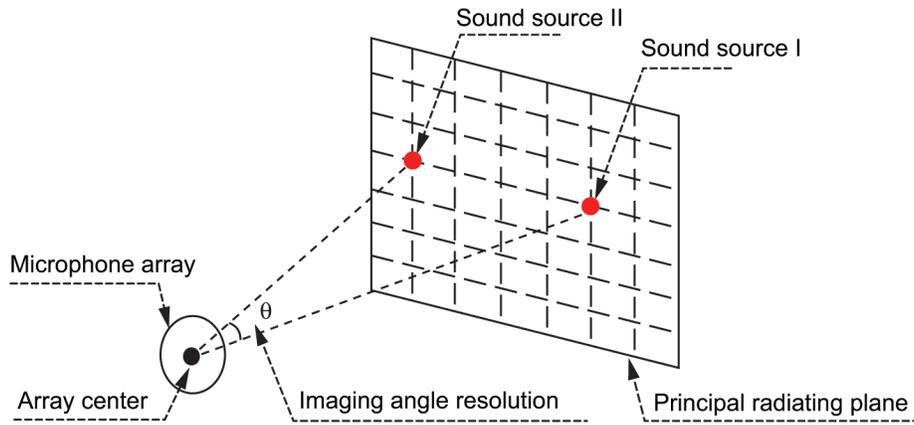


Figure 1—Schematic diagram of imaging angle resolution

localization error: The distance deviation between the actual center point of a sound source and the sound source position indicated in the sound field distribution nephogram on the principal radiating plane (see Figure 2). *See also:* **principal radiating plane; sound field distribution nephogram.**

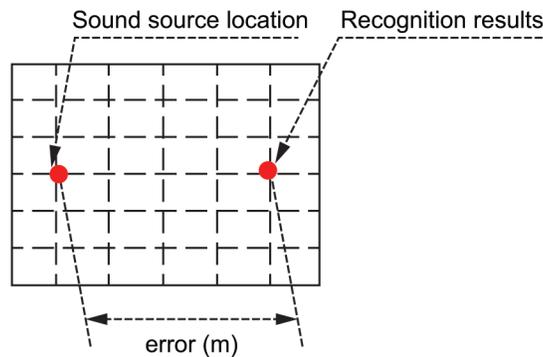


Figure 2—Schematic diagram of localization error

measurement distance: The distance between the measurement plane and the principal radiating plane, indicated by the symbol L . *See also:* **measurement plane; principal radiating plane.**

measurement plane: An acoustic signal receiving plane formed by a microphone array. *See also:* **microphone array.**

microphone array: An array composed of multiple microphones arranged according to a certain spatial geometric position used to collect acoustic signals in the space.

principal radiating plane: An imaginary plane parallel to the measurement plane and located at the equipment being tested. It is generally assumed that the acoustic signal is emitted from this plane. *See also:* **measurement plane.**

sound field distribution nephogram: A distribution result of the sound pressure levels of the acoustic signals reconstructed by a specific algorithm for the principal radiating plane. *See also:* **principal radiating plane.**

3.2 Acronyms and abbreviations

CBF	conventional beamforming
CLEAN-SC	clean based on spatial source coherence
DAMAS	deconvolution approach for the mapping of acoustic source
EVOB	eigenvalue optimization beamforming
SPL	sound pressure level

4. Test principles and instrument composition

4.1 Basic principle

The principle of an acoustic imaging test is shown in Figure 3. An acoustic imaging instrument (hereafter referred to as an *acoustic imager*) is arranged with the equipment being tested. The sound signals of multiple channels are received synchronously through a microphone array, and the sound field distribution nephogram on the principal radiating plane of the equipment is calculated according to an imaging algorithm. A visible-light image of the equipment being tested is synchronously recorded during the measurement as the background, and an acoustic imaging map is obtained by superimposing and displaying the sound field distribution nephogram on the visible light image through geometric registration. The acoustic imaging map intuitively shows characteristics including the sound source location and intensity.

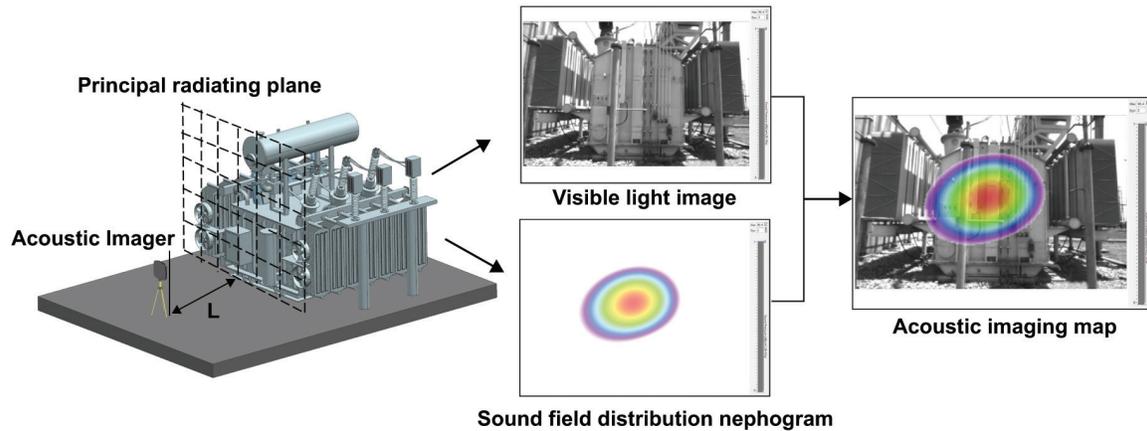


Figure 3—Detection principle for acoustic imaging test

4.2 Calculation principle for sound field distribution nephogram

A sound field distribution nephogram is usually calculated with the principle of a conventional beamforming (CBF) algorithm. The algorithm can take into account both near- and far-field testing. The basic principle is shown in Figure 4. The sound source point is located on the principal radiating plane. The microphone array is located on the measurement plane. Due to the difference in the distances between each microphone and the sound source point, there is a time delay Δt between the acoustic signals received by different microphones. The synchronously collected sound signals of each microphone are reconstructed for the principal radiating plane through delay summation, and all points are superimposed to obtain the sound field distribution nephogram of the principal radiating plane. If the microphone signals at this point are in the same phase, the signal amplitude increases significantly after superposition, and the main lobe is formed; if not in the same phase, sidelobes are

formed after superposition. In the sound field distribution nephogram, the main lobe corresponds to the sound source, and the sidelobes form virtual images. Please refer to [Annex A](#) for the detailed calculation process.

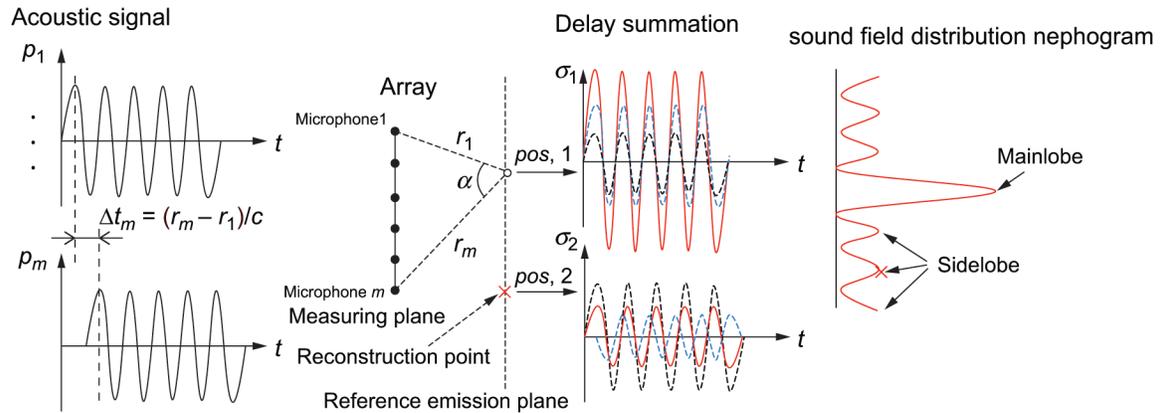


Figure 4—Basic principle of conventional beamforming (CBF) algorithm

4.3 System composition of the acoustic imager

4.3.1 General

The acoustic imager system is composed of sensing, data acquisition, and an analysis and display units, along with an auxiliary test instrument.

4.3.2 Sensing unit

The sensing unit includes the microphone array and cameras.

4.3.3 Data acquisition unit

The data acquisition unit mainly includes a multichannel data acquisition module and a data transmission line.

4.3.4 Analysis and display unit

The analysis and display unit mainly includes the software and hardware with functions such as real-time sound field calculation, image processing, and output display.

4.3.5 Auxiliary test devices

The auxiliary test devices include thermometers, hygrometers, anemometers, distance-measuring instruments, brackets, and so forth.

5. Application scenarios and test recommendations

5.1 Application scenarios

An acoustic imaging test provides relevant parameters for the acoustic signal of an operating reactor, including the sound pressure level, frequency spectrum, and acoustic imaging map of the equipment being tested. Based on different uses and application scenarios, acoustic imagers may be divided into the following types:

- a) *Live detection acoustic imager*: This type of acoustic imager usually involves movable detection that requires a battery power supply and generally has functions such as image display, video, audio playback, and storage. The imaging positioning accuracy is required to be high, and the image information such as the spectral characteristics and sound field distribution nephogram should be given in real time. This is mainly suitable for the on-site testing of reactors, including general testing as well as precise diagnosis and testing.
- b) *Online monitoring acoustic imager*: This type of acoustic imager may be installed or placed near the tested reactor for continuous real-time monitoring, transmitting the original signal and acoustic imaging maps to the host computer, and executing host computer instructions. It provides information such as the alarm, analysis, and diagnosis results based on the system requirements. It has an external power interface, which ensures a long-term, sustained stability in various complex use environment (including electromagnetic and meteorological environments). Its protection level exceeds IP54.
- c) *Onboard acoustic imager*: This type of acoustic imager may be placed on mobile carriers such as aircrafts, cars, and robots for autonomous or semi-autonomous inspections. It has wireless or wired data transmission, local storage, and other functions. It should provide information such as alarm, analysis, and diagnosis results according to requirements. The design may be easy to load on a mobile carrier, and the protection level is greater than IP54.

5.2 Field test environment recommendations

The recommendations for the surrounding environment of the on-site test are as follows:

- a) The ambient temperature should generally be in the range of $-10\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$, and the relative humidity is lower than 85%. When the conventional temperature and humidity ranges are exceeded, the testing personnel may confirm that the instrument can still operate normally.
- b) Tests may be conducted in good weather when the wind speed is below than 5 m/s.
- c) Attempts may be made to reduce enclosed obstructions (such as walls and baffles) in the sound propagation path.
- d) The influence of environmental interference sources on the test should be restrained by the following measures: selecting a good test period and location, adopting reasonable equipment operation control measures, and so forth.
- e) If there is any live equipment in the testing environment, it is noted that the test instruments and operators may keep a large enough electrical safety distance from any live equipment.

5.3 Instrument performance recommendations

5.3.1 Recommendations for microphones

Recommendations for microphones are as follows:

- a) The frequency range should be 20 Hz to 100 kHz.
- b) The dynamic range should be 36 dB to 110 dB.

5.3.2 Recommendations for microphone array

Recommendations for microphone array are as follows:

- a) The microphone array should have integrated and assembled types. The assembled type is simple to assemble and easy to carry.
- b) Each microphone array bracket should be made of non-metallic materials to meet the signal acquisition criteria and personal safety criteria in a high-voltage electromagnetic field test environment.
- c) Please refer to [Annex B](#) for the parameter selection for the array scanning angle, array aperture, and microphone interval (number of microphones).

5.3.3 Recommendations for cameras

Recommendations for cameras are as follows:

- a) The pixel resolution is greater than 640×480 pixels.
- b) The field angle recommendations are shown in [Annex B](#), which is consistent with the array acoustic imaging field angle.

5.3.4 Recommendations for the data acquisition unit

Recommendations for the data acquisition unit are as follows:

- a) The data acquisition unit has a synchronous acquisition capability of 60 channels and above. The number of channels of the data acquisition unit is consistent with the number of microphones, and it has synchronous acquisition ability.
- b) Each channel of the system has a 16-bit or a higher analog-to-digital converter.
- c) The sampling rate of each channel of the system is greater than twice the upper frequency of the microphone.

5.3.5 Recommendations for data processing analysis unit

Recommendations for the data processing analysis unit are as follows:

- a) The acoustic image refresh rate is not less than 30 frames per second.
- b) The data processing analysis unit at least has a CBF algorithm.
- c) The acoustic imaging localization error of the unit: The localization error from the 2 kHz sound source to the 2 m test distance is less than 50 mm.

5.3.6 Recommendations for working power supply

The instrument should support an electrical or battery power supply, and the continuous normal working time of a battery power supply is not less than two hours.

5.3.7 Recommendations for data storage

Recommendations for data storage are as follows:

- a) The data of the test results, including the videos, audios, and acoustic imaging maps are stored in general formats such as .mp4, .mp3, .wav, .jpg, and .png file formats.

- b) The data storage space is not less than 4 GB.
- c) The test data is exported by USB and other common interfaces.
- d) The test data is saved in general formats, such as .uff (universal file format), .dat, and .tdms (technical data management streaming).

5.3.8 Recommendations for data communication

Recommendations for data communication are as follows:

- a) Acoustic imagers used for online monitoring and live detection scenarios may have data communication functions to meet the recommendations of data transmission and command interaction, and the data transmission protocol should support Modbus RTU and/or IEEE Std C37.118.1-2011 and/or IEEE Std 1615-2007 and other common protocols.¹¹
- b) The acoustic imagers used in the airborne detection scene have the function of wireless data transmission to achieve the remote analysis and recording of data.

5.3.9 Other recommendations

Other recommendations of the testing instruments include the following:

- a) In order to reduce the influence of wind on the test results, the microphones should be equipped with a windshield or protective film during the test.
- b) The protection level of the acoustic imager is not lower than IP54.

5.4 Instrument functional recommendations

Instrument functional recommendations are as follows:

- a) *Acoustic imaging*: The instrument should image the acoustic signal and the visible light signal separately and automatically fuse and register the sound field distribution nephogram and the visible light image taken at the same location and at the same time, thereby achieving the localization and imaging of the sound source.
- b) *Spectral analysis*: The instrument has functions such as displaying the spectrum result in real time, spectrogram outputting, frequency weighting, and octave filtering; please refer to the IEEE Std 111-2000.
- c) *Sound pressure level test*: The instrument has a sound pressure level test function.
- d) *Display*: The instrument has the function of displaying the imaging results in real time, and the results should be clearly visible in the sunlight.
- e) *Adjusting the dynamic range of the imaging display*: The instrument has the function of adjusting the dynamic range of the imaging display to realize the need for control results accuracy and the observation effect in different test environments.
- f) *Adjustment of imaging frequency band*: The instrument should adjust the imaging frequency range in real time or preset multiple imaging frequency bands to realize the need for the imaging requirement of different characteristic frequencies.
- g) *Frame-by-frame play of the imaging picture*: The instrument should play the imaging picture frame by frame to realize the need to identify any transient sound source identification.

¹¹Information on references can be found in [Clause 2](#).

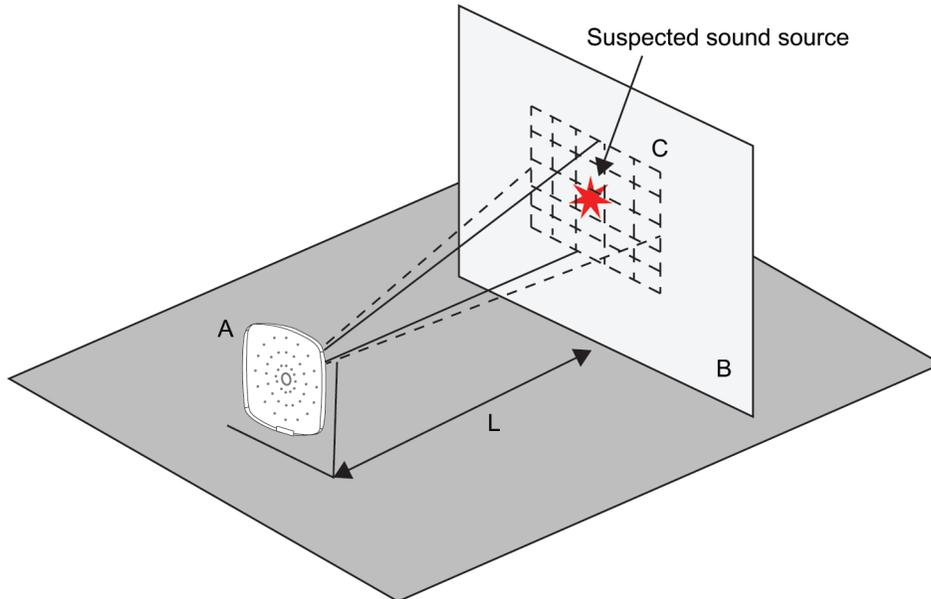
- h) *Recording and playback*: The instrument should record and output the results of the acoustic imaging, and it has video, audio recording, and output functions. The recorded test results are retrieved and reviewed at any time.
- i) *Others*: The instrument has the capability of software upgrade and function expansion.

6. Test implementation

6.1 Test recommendations

6.1.1 Test orientation

The measurement plane of the microphone array should face the equipment being tested so that the suspected sound source on the acoustic imager is near the center of the imaging area of the instrument and the equipment being tested or abnormal parts are displayed as completely as possible in the image of the acoustic imager. Additionally, attempts are made to keep away from obstructions in the propagation path. The test orientation is shown in [Figure 5](#).¹²



NOTE 1—A: measurement plane.

NOTE 2—B: principal radiating plane.

NOTE 3—C: imaging area.

NOTE 4—L: test distance.

Figure 5—Schematic diagram of test orientation

¹²Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

6.1.2 Selection of imaging frequency

When the spectrogram has a characteristic frequency (when the energy of the acoustic signal is concentrated in certain frequencies or frequency bands), the test frequency range of the acoustic imager may be adjusted to observe the imaging situation in different frequency ranges for sound source (such as vibration, loosening, and corona) analysis. When the reactor is in normal operation, the fundamental frequency of the acoustic signal is twice the frequency of the system, accompanied by harmonic characteristics. The acoustic imaging test may record the frequencies of at least three peak signals from large to small, with the corresponding peak frequency as the center frequency; the bandwidth is not higher than 100 Hz. The acoustic imaging analysis is conducted and the acoustic imaging maps of the fundamental frequency are recorded.

When abnormal vibration and discharge defects appear in the reactor, such as multifrequency characteristics of the sound source, it should intercept the sound signal data of the effective time period for analysis, select at least five peak signals frequencies from large to small, take the corresponding peak frequency as the center frequency, and conduct acoustic imaging analysis with the bandwidth not higher than 100 Hz; if the sound source is characterized by broadband, the frequency band with outstanding energy is selected for segment-by-segment imaging, and the width of a single frequency band is not higher 2000 Hz.

6.1.3 Interference elimination

The measurement positions are as far away from the interference source as possible.

- a) When the frequency characteristics of an interference source and the measured sound source are inconsistent, the interference source may be filtered by adjusting the frequency.
- b) When the time domain characteristics of an interference source and the measured sound source are inconsistent, the interference source may be filtered by adjusting the time frame.

6.1.4 Selection of the dynamic range of an imaging display

When there is interference at the test site, the dynamic range of the imaging display may be reduced to filter the background noise interference and increase the identification resolution of the main source of the sound. When there are multiple sources of sound at the test site, the dynamic range of the imaging display may be increased to discover other sources of sound. The dynamic range of the imaging display is between 1 dB and 6 dB. This selection of the dynamic range is affected by the characteristics of the on-site sound source and the precision and accuracy of the instrument test.

6.1.5 Selection of imaging algorithm

For the selection of an imaging algorithm, refer to [Annex A](#). Considering the recommendations of the instantaneity of imaging in a field test, a CBF algorithm is adopted.

6.1.6 Timing of test

The timing of test is as follows:

- a) At the initial stage of reactor operation, acoustic imaging tests are carried out to record basic data.
- b) Acoustic imaging tests are carried out regularly during the operation of a reactor. It is noted that the measurement positions are consistent.
- c) Tests are carried out when the sound increases in the reactor, abnormal acoustic signals occur in the reactor, or when there are other testing and diagnosis requirements.

6.2 Live detection process

6.2.1 General

The basic process of live detection mainly includes test preparation, measurement positions selection, test distance input, test duration setting, data acquisition and recording, and additional tests. The specific process is shown in Figure 6.

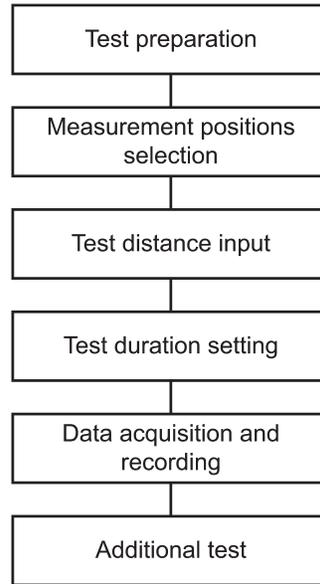


Figure 6—Live detection process

6.2.2 Test preparation

The test preparation steps include turning on the instrument and waiting for the system to stabilize, checking that the video collection is normal, and checking that the acoustic signal collection is normal.

If necessary, the imaging localization function of the acoustic imager should be self-checked before the test starts. It is advisable to use a reference sound source facing the measurement plane placed at a distance of 2 m. The reference sound source is located in real time. The localization error is not higher than 50 mm.

6.2.3 Measurement positions selection

The test orientations and the measurement positions are selected according to the procedure described in 6.1.1; the imaging area should be kept away from any source of sound interference as much as possible.

Measurement positions should be selected from different directions around the location of the reactor; measurement positions adjust the direction and angle of the measurement plane and determine and record at least one location with a good detection result. For reactors with cylindrical shapes, the measurement positions should be selected at three locations that are 120° apart from each other in the horizontal direction. For reactors with rectangular shapes, the measuring positions should be selected at four lateral locations perpendicular to the ground.

6.2.4 Test distance input

After the measurement positions is selected, the test distance in the instrument is measured and entered. The test distance is not more than 50 m and less than 0.7 times the array aperture. Refer to [Annex C](#) for the influence of the test distance input error on the imaging results.

6.2.5 Test duration setting

The test period should reflect the time characteristics of the sound signal and be more than 10 s.

When the sound source being tested is steady, the test should be collected when the background noise in the operating environment is stable.

When the sound source being tested is unsteady, the trigger test should be adopted, and the trigger parameters should be selected from sound pressure level or frequency. The collected data include the time period before and after the trigger.

6.2.6 Data acquisition and recording

The test is carried out after the working condition of the target being tested is stable.

Refer to [6.1.2](#) for the selection of the imaging frequency. When an abnormality is found, the test period, the measurement positions, and the result of the acoustic imaging should be recorded promptly; refer to [Annex D](#) for detailed recording content.

Data collection includes methods using continuous, periodic, or threshold-triggered logging. The trigger mode may be selected as the sound pressure level value trigger or another characteristic value trigger.

Classification tests should be carried out according to the reactor body and auxiliary device, and the data should be saved.

6.2.7 Additional test

Acoustic imaging additional test should be performed on reactor under the following conditions, including (but not limited to):

- a) When it is necessary to confirm abnormal parts and key test equipment, targeted close-range tests and verifications are conducted.
- b) When the characteristics of the sound source change with time, it is tested and verified at the same measurement positions.
- c) In order to verify that an abnormal sound source has been eliminated, the test and verification are carried out at the same measurement positions under the same working conditions.

6.3 Additional recommendations for online monitoring

For online monitoring, continuous monitoring is required. The specific process of online monitoring (shown in [Figure 7](#)) is as follows:

- a) *Measurement positions selection:* Long-term security and reliability are considered in online monitoring. According to [6.1.1](#), the test orientation and the measurement positions are selected and fixed, and the imaging area is kept away from sound interference sources as much as possible. In order to improve the detection effect, the monitored equipment is completely displayed on the imaging monitoring screen, and the geometric proportion of the equipment on the screen is greater than 80%.

- b) *Task creation*: The monitoring task management information is recorded such as the measurement positions, the name of the monitored equipment, the voltage level, and so forth.
- c) *Acquisition parameter setting*: According to different tested equipment, the corresponding acquisition parameters are determined, such as sampling duration, warning threshold, and so forth.
- d) *Data communication*: Data such as acoustic imaging results, spectrum results, and eigenvalue results are transmitted to the monitoring platform according to Modbus RTU and/or IEEE Std C37.118.1-2011 and/or IEEE Std 1615-2007 and other common protocols.
- e) *Diagnosis analysis*: Data is processed with the diagnosis algorithm and compared with historical data or preset thresholds to obtain the diagnostic results. Refer to [Clause 7](#) for specific analysis methods.
- f) *Abnormal alarm*: An alarm signal is issued for various abnormal states based on the obtained diagnostic results.
- g) *Regular verification*: It is necessary to regularly check the imaging positioning, data transmission, alarm, and other functions of the instrument to help ensure that the instrument detection and transmission are correct.

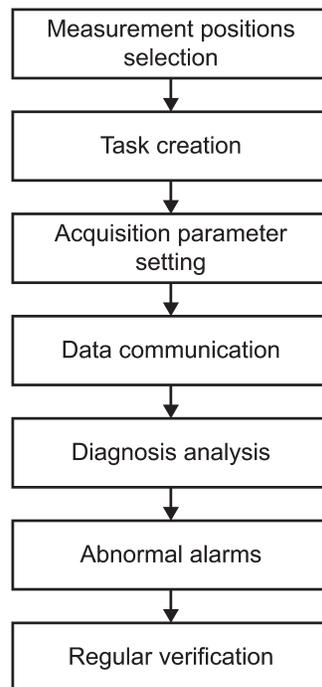


Figure 7—Online monitoring process

6.4 Additional recommendations for onboard detection

Onboard detection is carried out when the mobile carrier is stagnant. The specific process for onboard detection (shown in [Figure 8](#)) is as follows:

- a) *Measurement positions selection*: For the different reactors to be tested, the testing orientation and measurement positions may be selected according to their location in the substation as per recommendations stipulated in [6.1.1](#). Meanwhile, the minimum interference and maximum imaging area are used as a benchmark for the selection. It is necessary to display reactors to be tested in the imaging area entirely and have the geometric proportion of such reactors no less than 80% in the image.

Under special circumstances, such as under the influence of occlusions and so forth, efforts are made during testing to display such reactors in the imaging area to the greatest extent possible. At this time, it is necessary to keep testing parameters of various reactors consistent with their previous configuration.

- b) *Onboard detection path planning*: The shortest detection path that satisfies the aforesaid criteria for inspection and testing may serve as a benchmark to determine the optimal inspection path, according to the layout features of reactors in the substation or the condition surrounding the reactors that require major detection.
- c) *Acquisition parameter setting*: The corresponding acquisition parameters such as sampling duration and warning threshold may be determined based on types of equipment being tested.
- d) *Data communication*: Results of acoustic imaging maps, frequency spectrum, characteristic values, and other data are transmitted to onboard platform as per common protocols such as Modbus RTU, IEEE Std C37.118.1-2011, and/or IEEE Std 1615-2007. Onboard detection allows real-time transmission or timed transmission of data.
- e) *Diagnosis analysis*: Data is processed with the diagnosis algorithm and compared with historical data or preset thresholds to obtain the diagnostic result. Refer to [Clause 7](#) for specific analysis methods.
- f) *Abnormal alarm*: An alarm signal is issued for various abnormal states based on the obtained diagnostic results.
- g) *Regular verification*: It is necessary to regularly check the imaging positioning, data transmission, alarm, and other functions of the instrument to help ensure that the instrument detection and the data transmission are done correctly.

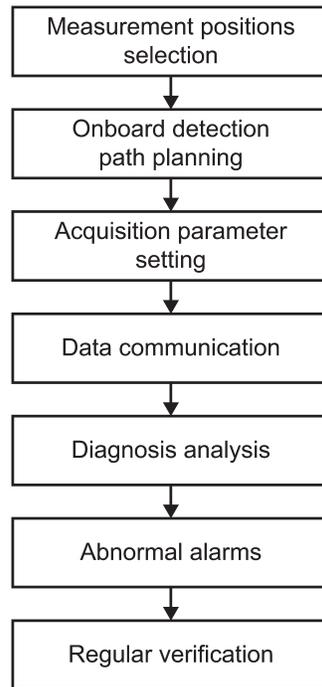


Figure 8—Onboard detection process

7. Analysis methods

7.1 Image characteristics analysis method

It is possible to analyze whether there are changes in the characteristics of the acoustic imaging map (such as the position, number, sound pressure level, and frequency of sound sources, etc.) of the same reactor at different times (or in different time periods), refer to the case in [E.1 of Annex E](#). If conditions for comparison are not met, the acoustic imaging map characteristics of reactors of the same type under similar working conditions may be compared for the analysis of device status (refer to the case in [E.2 of Annex E](#)). It is essential to rule out effects of various interference factors on image characteristics.

7.2 Comprehensive analysis method

It is possible to analyze whether changes occur in the characteristics of the acoustic imaging map and the spectral characteristics of acoustic signals (such as the frequency and the energy ratio under conditions with the maximum signal value, the energy ratio of the high-frequency section, etc.) of the same reactor at different times (or indifferent time periods), refer to the case in [E.3 of Annex E](#). If conditions for comparison are not met, the characteristics of the acoustic imaging maps and the acoustic signal spectrum characteristics of reactors of the same type under similar working conditions may serve as a reference for comparison. Based on variations in temperature, humidity, wind speed, interference sound sources, and other influencing factors, results of electrical tests or physical and chemical analyses are also examined during comprehensive analysis if necessary. This is generally used for the diagnosis and analysis of equipment complex defects/fault causes.

8. Data recording and reporting

A test report is completed that clearly defines information such as the tested equipment, test instrument, test condition, working condition of the test, measurement positions, and test result. The test report also includes the relevant content for the equipment, such as the acoustic imaging map, frequency spectrum characteristics, imaging frequency range, testing personnel, proofreader, reviewer, and similar information. Refer to [Annex D](#) for the specific content of a test report.

Annex A

(informative)

Principles of acoustic imaging algorithms

A.1 Principle of conventional beamforming algorithm

Assuming that a point sound source exists in the space, the sound source signal frequency is f , and the difference Δt_m between the times of the sound wave reaching a designated microphone of the microphone array and the reaching the other microphones are calculated using Equation (A.1) as follows:

$$\Delta t_m = \frac{(r_m - r_1)}{c} \quad (\text{A.1})$$

where

- r_1 is the distance from the sound source to the designated microphone
- r_m is the distance from the sound source to the m^{th} microphone
- c is the speed of sound in the air

Regardless of the noise in the environment, the signal received by any microphone unit in the microphone array may be calculated using Equation (A.2) as follows:

$$x_m = p(t) e^{j\omega\Delta t_m} \quad (\text{A.2})$$

where

- $p(t)$ is the sound pressure amplitude received by the microphone
- t is the time
- ω is the circular frequency of the sound source, and $\omega = 2\pi f$
- f is the frequency

The principal radiating plane is divided into a grid (Figure A.1).

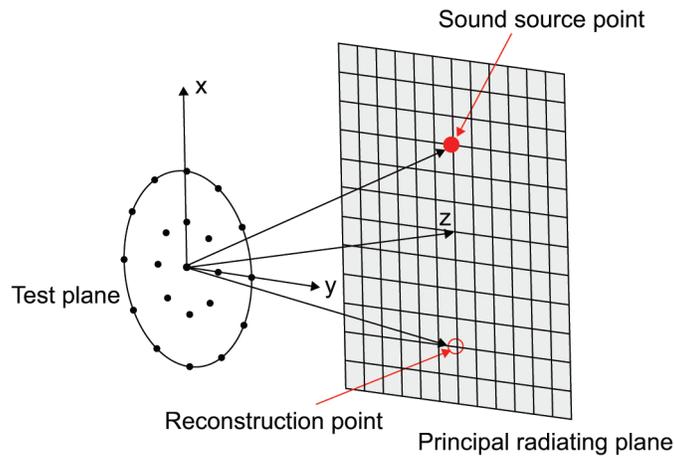


Figure A.1—Schematic diagram of beamforming principle

Assuming that each grid point is a sound source, for any point ζ in the grid, the sound pressure signal received by all array microphones is reconstructed for this point and the superimposed signal is represented by Equation (A.3):

$$B(r, t) = \frac{1}{M} \sum_{m=1}^M w_m p_m(t - \Delta t_\zeta) \quad (\text{A.3})$$

where

- M is the number of microphones in the array
- w_m is the weighting coefficient of the m -th microphone
- r is the distance from the reconstruction point to the microphone
- Δt_ζ is the difference between the times of the sound source at the point ζ in the grid reaching the reference element of the microphone array and reaching the other elements

In the actual localization process, it is necessary to locate the sources of sound of different frequency bands, so frequency domain processing is required. After the Fourier transform of Equation (A.3), the frequency domain expression of beamforming can be obtained, as shown in Equation (A.4) as follows:

$$B(r, \omega) = \frac{1}{M} \sum_{m=1}^M w_m p_m(\omega) e^{j\omega(\Delta t - \Delta t_\zeta)} \quad (\text{A.4})$$

It can be seen from the above formula that when $\Delta t = \Delta t_\zeta$, the compensated signals have the same phase, and the output value after weighted summation is the largest. When $\Delta t \neq \Delta t_\zeta$, the phases of the compensated signals are all different and cancel each other out when summing, and the output value is reduced. When $\Delta t \neq \Delta t_\zeta$, the beamforming outputs the maximum value, and a main lobe is formed in the sound field distribution nephogram. That is, the point ζ is considered the location of the sound source.

After calculation of the frequency domain, the $B(r, \omega)$ corresponding to all points of the grid of the principal radiating plane shown in Figure A.1 may be obtained. Then the sound field distribution nephogram of the principal radiating plane can be formed, thereby intuitively determining the specific location of the sound source.

A.2 Selection of acoustic imaging algorithms

One of the most important aspects of microphone-based acoustic imaging test technology is the selection of imaging algorithms. Different algorithms have various characteristics. To meet the criteria of abnormal noise testing of reactors, the basic processing algorithms of acoustic imagers include a conventional beamforming (CBF) algorithm, which includes an eigenvalue decomposition optimization algorithm [eigenvalue optimization beamforming (EVOB)], deconvolution acoustic imaging algorithm [deconvolution approach for the mapping of acoustic source (DAMAS)], clean based on spatial source coherence (CLEAN-SC) algorithm, and other optimization algorithms whose characteristics are shown in Table A.1.

Table A.1—Characteristics of four acoustic imaging algorithms

Name of algorithm	Advantage	Disadvantage	Application scenarios
CBF	Stability, high calculation efficiency	Low accuracy	Rapid acoustic imaging
EVOB	Stability, higher accuracy than the CBF algorithm	Slow calculation efficiency	On most occasions, do not have real-time requirements
CLEAN-SC	Higher accuracy than the EVOB algorithm	Poor recognition of coherent sources of sound and slow calculation efficiency	Incoherent sound source, aerodynamic noise, friction noise
DAMAS	Higher accuracy than other algorithms	Extremely slow calculation efficiency	Small component that requires high recognition accuracy

Annex B

(informative)

Technical parameter selection

B.1 Microphone array characteristics

The performance of a beamforming microphone array is mainly embodied in three aspects: imaging angle resolution, cut-off frequency, and effective dynamic range of the imaging display. The imaging angle resolution is mainly affected by the width of the main lobe. The narrower the main lobe is, the higher the resolution is. The angle between the two sources of sound that may be accurately distinguished on the principal radiating plane is characterized as the imaging angle resolution. According to the Rayleigh criterion, as seen in Equation (B.1) as follows:

$$R(\theta) = 2\arctan\left(\frac{\alpha \cdot \lambda}{2 \cdot D \cdot \cos^3 \theta}\right) \quad (\text{B.1})$$

where

- α is the array coefficient, which is $\alpha = 1$ for linear arrays and $\alpha = 1.22$ for planar arrays
- λ is the wavelength of the sound source signal, $\lambda = c/f$

The resolution R is related to the array aperture D , the sound source signal frequency f , and the array scanning angle θ . The larger D or f is, the smaller θ is, and the higher the resolution becomes. The cut-off frequency is caused by an aliasing phenomenon and is the highest frequency at which the beamforming algorithm can accurately identify the signal. The higher the numerical value, the better. The cut-off frequency equation is derived from the spatial sampling theorem, as seen in Equation (B.2) as follows:

$$f_{\max} = \frac{c}{d(1 + \sin\theta)} \quad (\text{B.2})$$

The larger the array scanning angle θ and the minimum microphone interval d is, the lower the cut-off frequency is.

B.2 Selection of typical parameters of array

B.2.1 Selection of array scanning angle

Converting the imaging angle resolution to the distance between the two sources of sound that may be accurately distinguished on the principal radiating plane; the following expression can be derived from Equation (B.3) as follows:

$$R_L(\theta) = \frac{\alpha \cdot L \cdot \lambda}{D \cdot \cos^3 \theta} \quad (\text{B.3})$$

where

- L is the distance between the measurement plane and the principal radiating plane

When λ , D , and L are fixed and the array scanning angle $\theta = 0^\circ$ Equation (B.4) is obtained. At this time, the axial resolution of the array R_{Axis} is the smallest and the resolution is the highest.

$$R_{\text{Axis}} = \frac{a \cdot L \cdot \lambda}{D} \quad (\text{B.4})$$

It can be determined from Equation (B.5) that at this time, the array resolution R decreases sharply with an increase of the array scanning angle θ (Figure B.1). The imaging angle resolution at $\theta = \pm 30^\circ$ is 53.96% lower than that at 0° , and the array scanning angle θ is usually within the range of -30° to 30° .

$$\frac{R(\theta)}{R_{\text{Axis}}} = \frac{1}{\cos^3 \theta} \quad (\text{B.5})$$

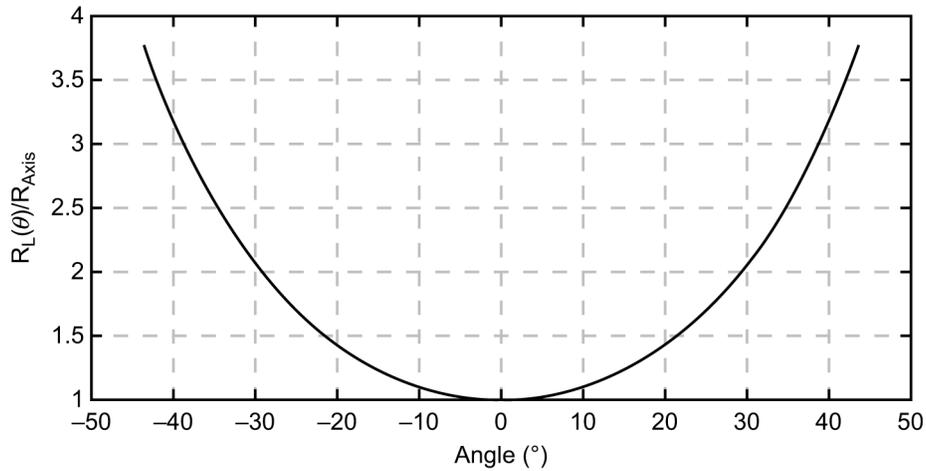


Figure B.1—Trend of acoustic imaging resolution with field of view

B.2.2 Selection of array aperture

When the imaging angle resolution is $R = 30^\circ$ and the array scanning angle is $\theta = 0^\circ$, the relationship between the array aperture size D and the lower limit of the sound source identification frequency f is as shown in Table B.1. The lower the identification frequency limit is, the larger the required array aperture is. The actual field of view during on-site detection is greater than 0° , Therefore, the required array aperture is greater than the associated value in Table B.1.

Table B.1—The relationship between the array aperture and the lower limit of the identification frequency

f/Hz	D/m	f/Hz	D/m	f/Hz	D/m
100	7.7403	600	1.2900	2000	0.3870
200	3.8701	700	1.1058	3000	0.2580
300	2.5801	800	0.9675	4000	0.1935
400	1.9351	900	0.8600	5000	0.1548
500	1.5481	1000	0.7740	6000	0.1290

B.2.3 Determination of microphone interval

The microphone interval d is affected by the array aperture size D and the number of microphones M . The relationship between the microphone interval d and the upper limit of the identification frequency f is shown in [Table B.2](#). The smaller the microphone interval d is, the higher the upper limit of the identification frequency f is. The method of increasing the number of microphones M is generally used to obtain the ability to recognize high-frequency bands.

Table B.2—The relationship between the microphone interval and the upper limit of the identification frequency

f/Hz	d/m	f/Hz	d/m	f/Hz	d/m
1000	0.3400	8000	0.0425	15 000	0.0227
2000	0.1700	9000	0.0378	16 000	0.0213
3000	0.1133	10 000	0.0340	17 000	0.0200
4000	0.0850	11 000	0.0309	18 000	0.0189
5000	0.0680	12 000	0.0283	19 000	0.0179
6000	0.0567	13 000	0.0262	20 000	0.0170
7000	0.0486	14 000	0.0243	21 000	0.0162

B.2.4 Selection of the array dynamic display range

The dynamic display range of the array is defined as the difference between the maximum side lobe value and the peak value of the main lobe, which is mainly related to the arrangement of the microphones in the array.

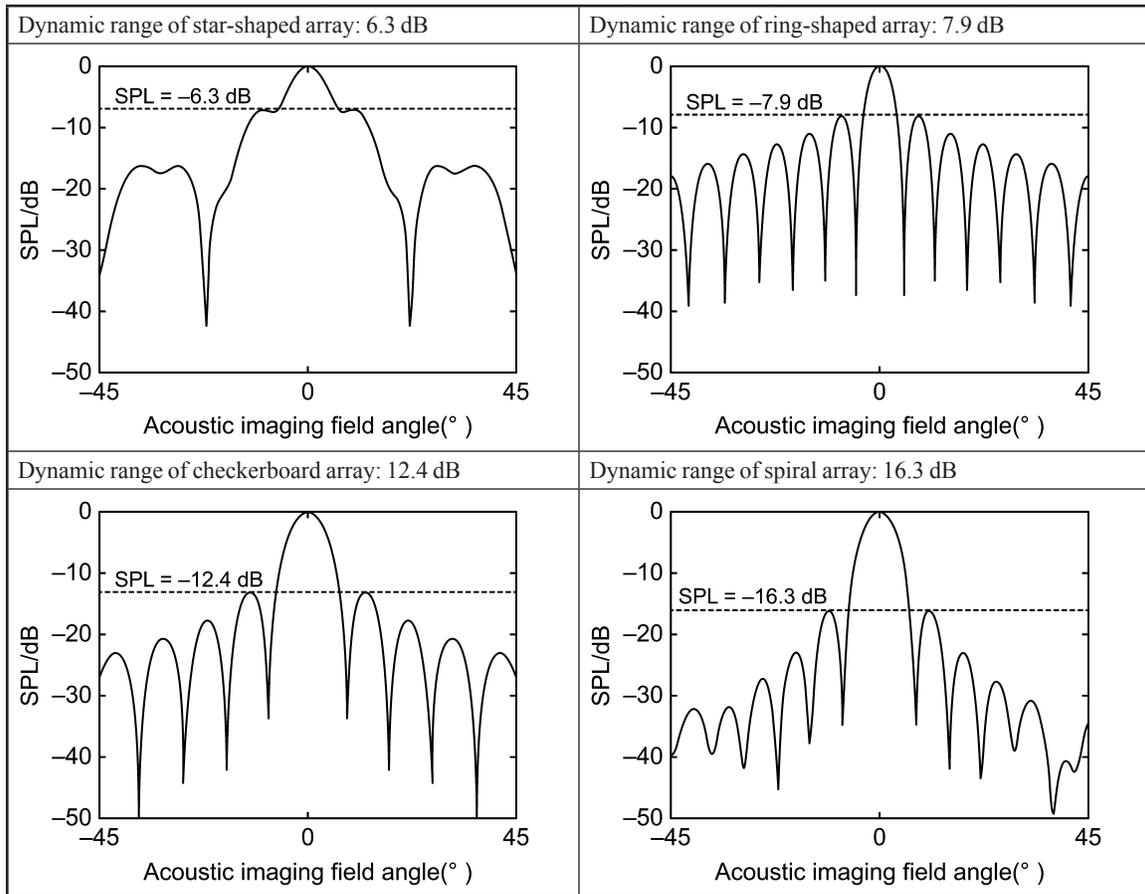
The calculation results for the response maps of the microphone arrays in different arrangements in [Figure B.2](#) are shown in [Figure B.3](#). As shown in [Figure B.2](#), the star-shaped, ring-shaped, and checkerboard arrays are uniformly arranged, and the spiral is non-uniformly arranged. The intervals between the nearest adjacent microphones are 0.04 m, the array aperture in the analysis is 0.6 m, and the microphone intervals of the uniform array are 0.04 m.

For the same array aperture and microphone spacing, the number of microphones required for star, ring, spiral, and checkerboard arrays increases in turn. Among these arrays, a spiral and a checkerboard require 112 and 256 microphones, respectively, and the number of array elements required for these two array shapes far exceeds that for other structures.

The results of the array response maps show that the star and ring arrays have more side lobes, while there are relatively few side lobes for the checkerboard and spiral arrays, indicating that the checkerboard and spiral arrays have relatively good anti-interference abilities. As shown in [Figure B.3](#), the sound source frequency is 5 kHz, the distance from the test plane to the sound source plane is 1 m, and the image in the figure shows a dynamic range of 15 dB. The helical array has no false sources of sound within the display range of 15 dB and is more suitable for accurately identifying the position of the real sound source in a complex acoustic environment.

For the same microphone aperture, the spiral-shaped array features the best and most effective dynamic recognition range. [Table B.3](#) shows the numerical results of the effective dynamic range of different arrays. It may be seen that the dynamic range of the star-shaped array is the smallest at only 6.3 dB. The dynamic ranges of the ring-shaped and checkerboard-shaped arrays are the next smallest at 7.9 dB and 12.4 dB, respectively. The effective dynamic recognition range of the spiral-shaped array is the largest, reaching 16.3 dB.

Table B.3—Comparison of the effective dynamic ranges of different arrays



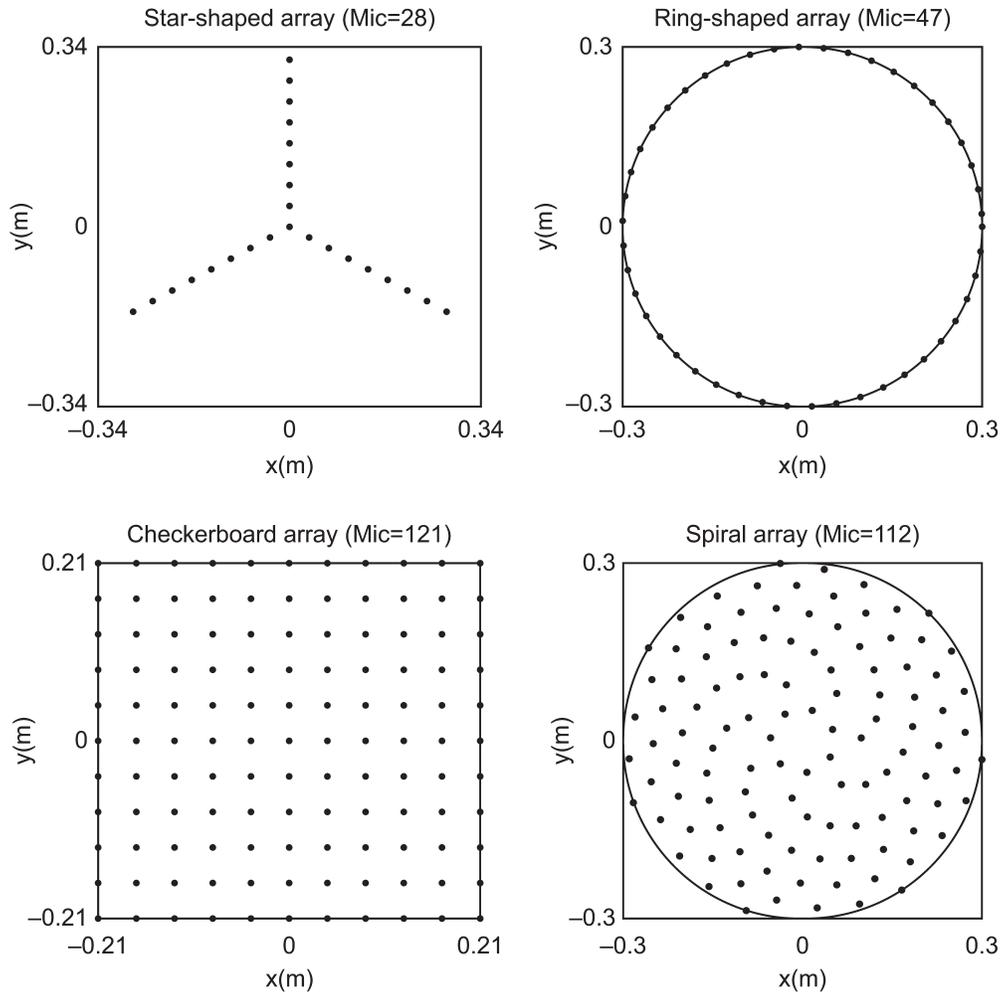
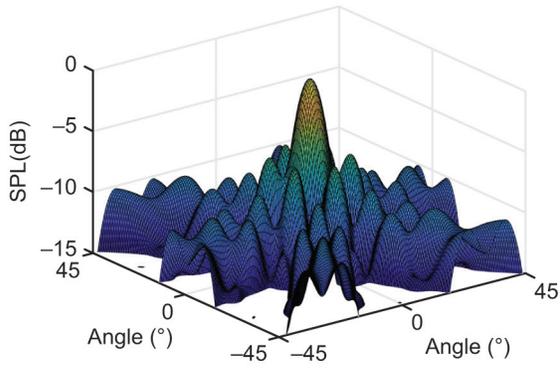
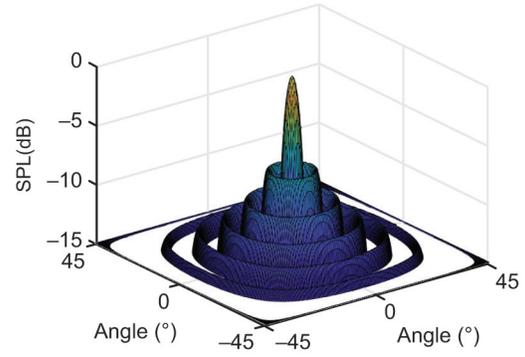


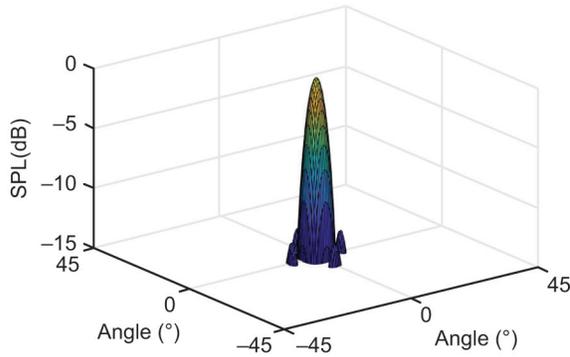
Figure B.2—Schematic representation of array models with different shapes



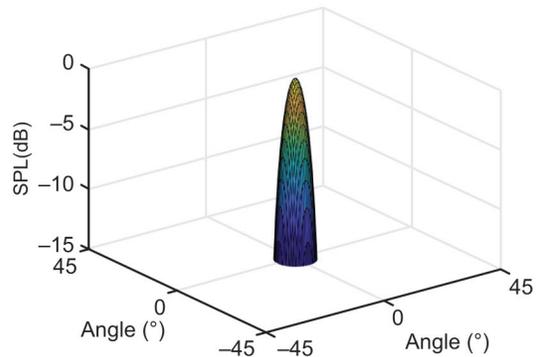
(a) star-shaped array



(b) ring-shaped array



(c) checkerboard-shaped array



(d) spiral-shaped array

Figure B.3—Array response three-dimensional spectrum

Annex C

(informative)

The influence of the detection distance on the test results

C.1 General

In actual testing, the test distance is often difficult to accurately determine. The influences of the test distances on the test results are divided into the influences on the test sound pressure level and the influences on the acoustic imaging maps.

C.2 Influences on test sound pressure level

Assuming that the actual sound source distance is r , when the error between the input calculated distance and the actual sound source distance is $a\%$, it may be determined from the spherical wave expansion that the sound pressure level (SPL) test error ΔL_p can be expressed as follows in Equation (C.1):

$$\Delta L_p = 20 \cdot \log_{10}(1 + a\%) \quad (\text{C.1})$$

Table C.1 shows the calculation of the SPL test errors for different distance errors using Equation (C.1). It can be seen from Table C.1 that the more accurate the input distance is, the more accurate the SPL calculation result is.

Table C.1—Sound pressure level test errors for different distance errors

Distance errors (%)	-50	-40	-30	-20	-10	0	10	20	30	40	50
Sound pressure level test errors (dB)	-6.02	-4.44	-3.10	-1.94	-0.92	0.00	0.83	1.58	2.28	2.92	3.52

C.3 Influences on localization results

The incoming waves of the sources of sound can be divided into near-field spherical waves and far-field plane waves. Calculations based on near-field spherical waves may use distance parameters as variables and scan and reconstruct for the principal radiating plane, while plane waves, as simplified spherical waves, may ignore the influence of the distance factor. Therefore, for either a spherical or plane wave, the input test distance is not an amount that needs to be accurately determined for the localization calculation. However, inputting the correct test distance helps to shorten the time for the localization calculation.

Annex D

(informative)

Reference format for acoustic imaging test records

The report of the acoustic imaging test for reactors includes content such as the tested reactors, test instrument, test condition, working condition of the test, measurement positions, and test results. For detailed content and format, please refer to [Table D.1](#).

Table D.1—Acoustic imaging test record of reactors

Substation name					
Equipment name		Equipment voltage level		Equipment operation number	
Equipment model		Manufacturer		Production/operation time	
Main test instruments	Acoustic imager	Anemometer	Temperature and humidity meter	Rangefinder	
Instrument model					
Instrument number					
Instrument validity					
Wind speed			Weather		
Temperature			Humidity		
Test time	Year month day hour minute		Test period		
Equipment load			Test distance input value		
Working condition of test	Preferably including but not limited to: Reactor: bus voltage, and oil temperature (if any)				
Measurement positions:					
Schematic diagram of measurement positions:					
Test site photos:					
Test result					
Imaging frequency band		Maximum sound pressure level	dB	Dynamic range of imaging display	dB
Acoustic imaging map: (refer to Annex E)					
Spectrum and acoustic chromatogram (if any): (refer to Annex E)					
Test conclusion:					
Tester:		Proofreader:		Reviewer:	

Annex E

(informative)

Acoustic imaging test cases for reactors

E.1 Abnormal sound detection of reactors in the converter station

Some abnormal sounds were heard adjacent to the B phase of a reactor in a converter station. The area with abnormal sounds was detected using an acoustic imager (Figure E.1). The detected acoustic imaging results were then compared with those obtained from the same device under normal operating state (see Figure E.2). This figure shows that the source of abnormal sounds were identified at an attachment of the reactor (in the abnormal state) on the device. Hence, the device was initially diagnosed with faults.

The B phase of the reactor was inspected when power had been cut off. A severe loosening of bolts of phase B of the reactor and loose wires were identified at the source of abnormal sounds (the on-spot fault inspection is shown in Figure E.3). This was consistent with results of acoustic imaging analysis. After the bolts were replaced and other structural connections were checked and tightened, the reactor was put into service again without emitting any abnormal sounds.

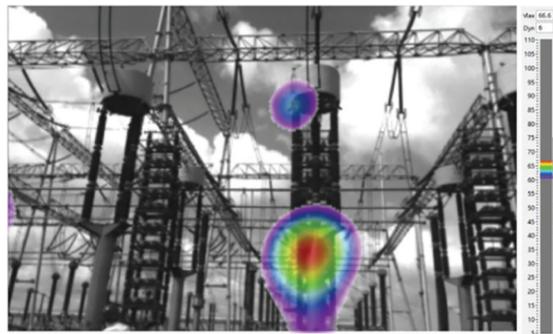


Figure E.1—Acoustic imaging test result of reactor in the abnormal state

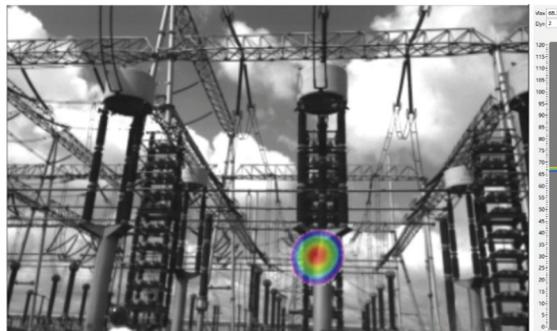


Figure E.2—Acoustic imaging test result of reactor in the normal state



Figure E.3—Schematic diagram of fault location

E.2 Abnormal sound detection of dry hollow reactors

A reactor in a substation produced some abnormal sounds during its operation. The area with abnormal sounds was detected using an acoustic imager (Figure E.4). The abnormal sounds came from the B phase of the reactor. The A, C, and B phases were from devices of the same model. No abnormal sounds were generated in areas with A and C phases. The B phase was initially diagnosed with faults.

The B phase of the reactor was tested repeatedly at close range using an acoustic imager. The acoustic imaging results are shown in Figure E.5. This figure shows that the source of abnormal sounds is at the bottom supporting bar. After the bolts were replaced and their supporting bars were checked and tightened, the reactor was put into service again without emitting any abnormal sounds.

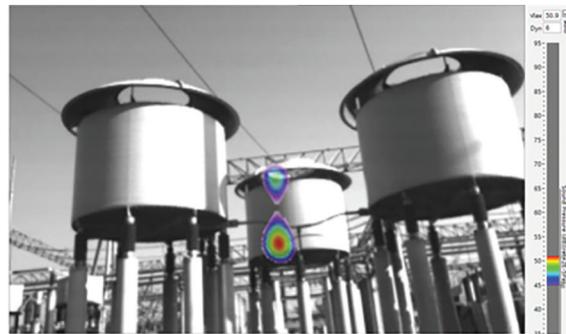


Figure E.4—Acoustic imaging test result of reactor at long-range

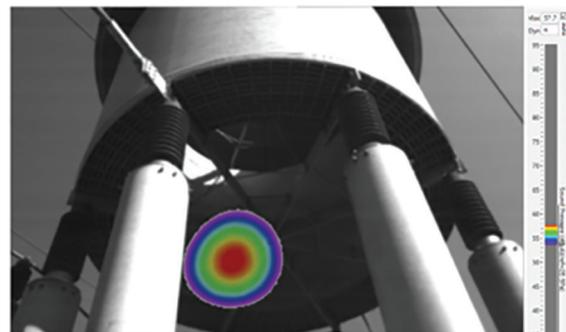


Figure E.5—Acoustic imaging test result of reactor at close-range

E.3 Abnormal sound detection of oil-immersed reactors

Near the A phase of a reactor in a substation, some abnormal sounds were occasionally but intermittently heard. The acoustic chromatograms of the reactor in the normal and abnormal states after testing are shown in Figure E.6 and Figure E.7. Figure E.6 shows that the acoustic signal of the reactor in the normal state is mainly below 2 kHz; Figure E.7 indicates that the acoustic signals of the reactor with abnormal sounds were found with pulse waveforms and at high frequencies of up to 10 kHz. Based on a calculation of acoustic imaging at normal and abnormal sound frequency bands (The imaging frequency range is 2500 Hz to 3500 Hz), the derived acoustic imaging test results in the normal and abnormal states are shown in Figure E.8 and Figure E.9, respectively. Figure E.8 indicates that under the same calculation frequency band, the reactor in the normal operating state produces no significant abnormal sounds. Figure E.9 shows that the abnormal sounds of the reactor mainly came from the grading ring. This portion was initially diagnosed with faults.

A reactor was checked when the power had been cut off. It was found that all supporting bars in the grading ring of the reactor had detached, and the grading ring was filled with water (the on-spot fault inspection is shown in Figure E.10). This was consistent with results of acoustic imaging analysis. After the grading ring of the reactor were replaced and checked again, the reactor was put into service again without emitting any abnormal sounds.

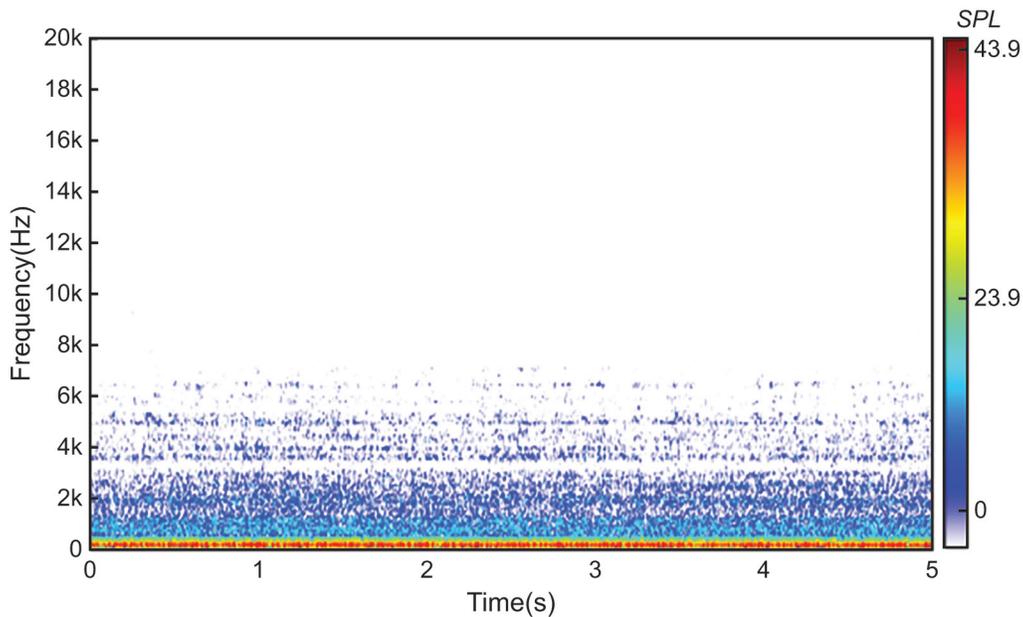


Figure E.6—Acoustic chromatogram of reactor in the normal state

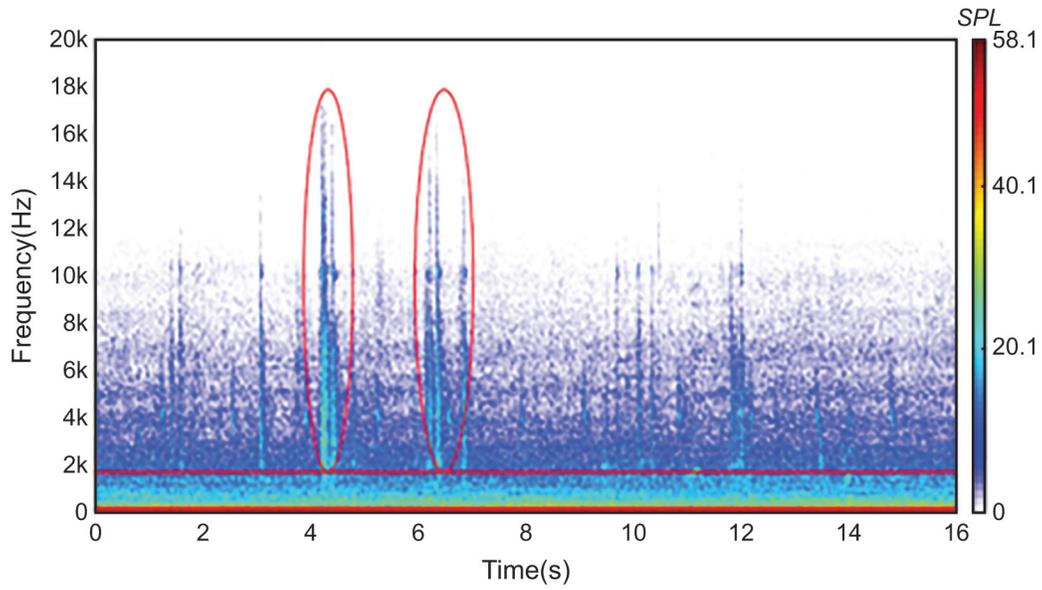


Figure E.7—Acoustic chromatogram of reactor in the abnormal state

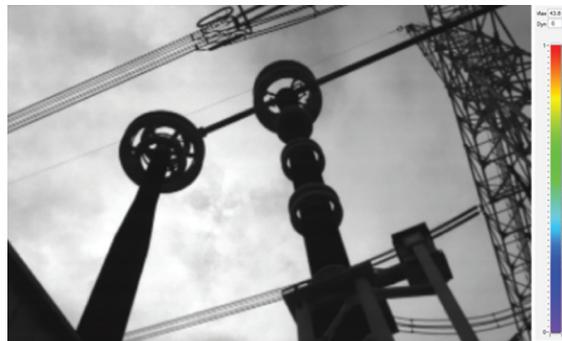


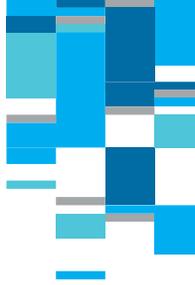
Figure E.8—Acoustic imaging test result of reactor in the normal state (Imaging frequency range 2500 Hz to 3500 Hz)



Figure E.9—Acoustic imaging test result of reactor in the abnormal state (imaging frequency range 2500 Hz to 3500 Hz)



Figure E.10—Schematic diagram of fault location



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