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Condition monitoring and diagnostics of machines — Ultrasound —

Part 1: General guidelines

Surveillance des conditions et diagnostic d'état des machines — Ultrasons —

Partie 1: Lignes directrices générales

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 29821-1 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 5, *Condition monitoring and diagnostics of machines*.

ISO 29821 consists of the following parts, under the general title *Condition monitoring and diagnostics of machines — Ultrasound*:

— *Part 1: General guidelines*

The following part is planned:

— *Part 2: Procedures and validation*

Introduction

This part of ISO 29821 provides guidance for the condition monitoring and diagnostics of machines using airborne and structure-borne ultrasound (A&SB ultrasound). A&SB ultrasound can be used to detect abnormal performance or machine anomalies. The anomalies which are detected are high-frequency acoustic events caused by turbulent flow, ionization events, and friction, which are caused, in turn, by incorrect machinery operation, leaks, improper lubrication, worn components or electrical discharges.

A&SB ultrasound is based on measuring the high-frequency sound that is generated by turbulent flow, by friction or by the ionization created from the anomalies. The inspector therefore requires an understanding of ultrasound and how it propagates through the atmosphere and through structures as a prerequisite to the creation of an A&SB ultrasound programme.

Condition monitoring and diagnostics of machines — Ultrasound —

Part 1: General guidelines

1 Scope

This part of ISO 29821 outlines methods and requirements for carrying out condition monitoring and diagnostics of machines using airborne and structure-borne ultrasound. It provides measurement, data interpretation, and assessment criteria. This technique is typically carried out on operating machinery under a range of conditions and environments. This is a passive technique that detects acoustic anomalies produced by machines.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and the following apply.

3.1
airborne and structure-borne ultrasound
A&SB ultrasound
non-destructive test method used to inspect for airborne and structure-borne ultrasound above 20 kHz created from or through a medium

3.2
background noise
unwanted noise present in a signal which cannot be attributed to a specific cause

[ISO 13372:—[1], 5.2]

NOTE This ultrasonic noise can emanate from the area surrounding the inspection which can cause false indications.

3.3
scanning
moving a receiving transducer or an array of transducers around a suspected source of ultrasound to verify the location

3.4
sonic reflection
airborne ultrasound reflected off a solid surface possibly indicating a false reading

3.5
stethoscope module
waveguide in the form of a rod that is coupled to a receiving transducer that receives ultrasounds by making physical contact with the subject and test equipment, for structure-borne ultrasounds

4 Principle of the airborne and structure-borne method

Airborne and structure-borne ultrasound is a physical wave that occurs within, or on the surface of, the test subject (material or machinery component) and is detected externally either close to or at a distance from the test subject. This technology is based on the detection of high-frequency sounds. Most ultrasonic instruments employed to monitor equipment detect frequencies above 20 kHz, which is above the range of human hearing (20 Hz to 20 kHz). The differences in the way low-frequency and high-frequency sounds travel helps to explain why this technology can be effective for condition monitoring. Low-frequency sounds maintain a high intensity of sound volume and travel further than high-frequency sounds. High-frequency sounds are more directional. As high-frequency sound waves propagate from the point of generation, their intensity level decreases rapidly with distance depending on the elasticity and density of the medium traversed, which helps to identify the origin of a sound source.

Airborne ultrasound is propagated through an atmosphere (air or gas) and detected with an ultrasonic microphone while structure-borne ultrasound is generated within and propagated through the structure, and is usually detected with a stethoscope (contact) module, although other sensors may be used. These stethoscope modules do not require any coupling agent, as the detection frequencies are low enough that, unlike traditional pulse-echo ultrasound, small air gaps between the contact probe and the structure under test do not significantly attenuate the received signal. If permanently mounted sensors are used, careful mounting techniques should be utilized to avoid signal attenuation or resonances, or both. The structure may be a machine or any component of a machine or a system.

5 Applications of the ultrasound method

Airborne and structure-borne ultrasound can be applied to a wide range of applications of equipment or machinery. Any equipment or machinery that produces turbulent flow, ionization or friction produces ultrasound. Table 1 shows typical examples of ultrasound applications to machine condition monitoring.

6 Training requirements

When performing ultrasound inspections under less-than-ideal conditions with considerable background noise, the confidence in the information obtained is dependent upon the training and experience of the practitioner and the detection method applied. The skills and expertise of the practitioner performing the measurements and analysing the data are critical to the effective application of ultrasound[1)]. A skilled practitioner shall utilize the proper shielding techniques for minimizing the background ultrasound noise and incorporate methods and procedures that lead to reliable inspection results.

1) ISO 18436-8[5] will specify the requirements for qualification and assessment of personnel who perform machinery condition monitoring and diagnostics using ultrasound.

Table 1 — Ultrasonic application examples

Machine description	Pressure or vacuum leak detection[a]	Mechanical[a]	Electrical[a]
Heat exchangers	AB	—	—
Boilers	AB	—	—
Condensers	AB	—	—
Control air systems	AB	—	—
Valves	SB	—	—
Steam traps	SB	—	—
Motors	—	SB	SB
Pumps	AB	SB	SB
Gears/gear boxes	—	SB	—
Fans	—	SB	—
Compressors	AB	SB	SB
Conveyors	—	SB	—
Switchgear	—	AB	AB
Transformers	—	SB	AB/SB
Insulators	—	—	AB
Junction boxes	—	—	SB
Circuit breaker	—	—	SB
Turbines	AB	SB	—
Generators (utility)	AB	SB	AB/SB
Lubrication	—	SB	—
High-speed bearings	—	SB	—
Low-speed bearings	—	SB	—

[a] AB: airborne; SB: structure borne.

7 Ultrasound equipment

A&SB ultrasonic detection instrument systems are typically hand held, portable and battery operated for ease of use in the field. Online, non-portable systems are also utilized mainly for condition monitoring where an anomaly can occur and shall be addressed at the inception rather than when a route-based inspection is scheduled. Most online applications target a narrow range of applications where amplitude is the primary parameter that is monitored and false indications are less likely to occur. It is recommended that the system consist of an instrument, ultrasonic transducers, and headphones. It is highly recommended that the demodulated signal output be appraised through headphones to enable discrimination between competing sources. This allows the practitioner to recognize and prevent the acquisition of poor quality data. The system shall provide for the detection of acoustic energy that is either airborne or structure borne in the range above 20 kHz and shall translate (demodulate) this energy into an audible signal that can be seen on a signal strength indicator and heard through the headphones. The signal strength is usually displayed in decibels and commonly referred to as "decibel value". The demodulated signal is representative of the amplitude and frequency characteristics of the original ultrasonic signal. The ultrasonic physical pressure wave or pressure variation which is received and measured by the ultrasound instrument is demodulated and converted to a corresponding level having the unit decibel (not standard definition); a sound pressure level, L_p, referenced to the threshold level of the A&SB ultrasound instrument where the mathematical expression is: L_p dB = 20 $\log_{10} r_\text{a}$, where r_a is the amplitude ratio.

Currently, instrument sensitivity varies because each manufacturer establishes its own threshold level (0 dB) as there are no standards to uniformly define this threshold level. There are also different levels of sensitivity for different instruments produced by a single manufacturer. Most condition-monitoring applications of this technology are based on comparison or trending of signal strength readings over time, so care should be taken to use instruments that have the same sensitivity so that comparable data can be obtained.

The main housing contains ultrasonic transducers that receive the ultrasound signal and convert it to an amplified electrical signal. Next, this signal is fed into the main instrument where it is amplified again, then demodulated or heterodyned. The demodulation (heterodyne) principle is used to convert the ultrasonic frequencies down to the audible level suitable for humans to hear and for interfacing with recording and analysing devices. The same principle is used in AM radio broadcasting and reception. In the demodulation or heterodyne process, the audio signal is a direct translation of the original signal and this demodulated signal is used for further analysis (see Figure 1).

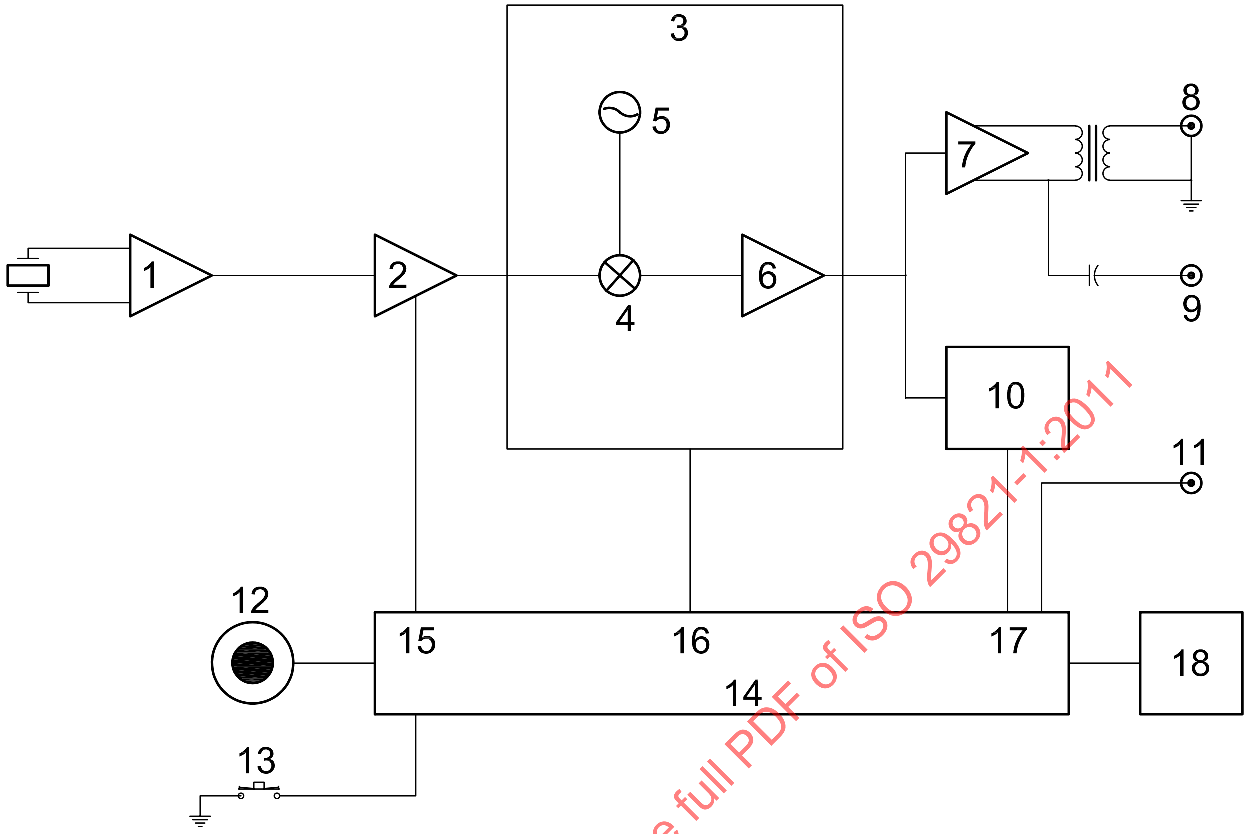
The demodulated signal allows the inspector to identify a relevant sound source and to determine the event or condition producing the ultrasound (e.g. air leaks in the same area as an electrical discharge can cause confusion to an unskilled inspector). The demodulated signal can also be used to determine the location of the irrelevant ultrasound that could lead to a false reading.

Therefore, the headphone output signal is not a “divided” signal where the audio frequency is multiplied by a number and ends up with the ultrasonic frequency. In the demodulation (heterodyne) process, the incoming ultrasonic signal is mixed with an internal oscillator signal and the difference is amplified and then sent to the headphone output and the meter circuit. A good analogy would be a piano key being struck once a second (1 Hz); the resultant sound would contain the resonant frequency of the string that the piano key is linked to, modulated by the 1 Hz of the key being struck. If the piano string signal (carrier frequency) were removed, what would be left is the 1 Hz signal (modulation frequency) of the key being depressed.

The ultrasonic detection modules only detect high-frequency noise caused by friction or turbulent flow and do not respond to low-frequency acceleration, displacement or audible sounds. In the case of bearings, ultrasound is created by the motion of the rotating elements. As a bearing deteriorates, defects form on the rotating surfaces and when a rotating element interacts with the defect, it produces an acoustic event or fault indication. The actual fault frequencies of the affected bearing modulate the high-frequency components of the generated ultrasonic noise or signal. The signal after the demodulation would only leave the original modulation. For example, in a bearing, if the fault frequency is 48 Hz, the instrument detects the ultrasonic component that is modulated by the 48 Hz fault frequency. When that signal is demodulated, the audio signal at the headphones does not contain the ultrasonic signal, but contains the 48 Hz fault-frequency signal.

In high-speed bearings, if one were to analyse the demodulated ultrasound signal with a spectral (FFT) analyser, and compare it to the signal from an accelerometer, the signals would be qualitatively similar. With low-speed bearings at speeds typically below 100 r/min, standard vibration accelerometers would have low signal strength due to the lack of enough energy to stimulate the piezoelectric sensing element with the calibration mass attached. For example, there are sensors currently used in mining operations to provide a signature from a 16,8 m diameter bearing operating at a speed less than 1 r/min for input from an ultrasonic detector into a portable FFT analyser for analysis and archival.

In addition to mechanical condition analysis, spectrum analysis of the heterodyned signals received from electrical discharges can help identify the severity of the condition, and can also help distinguish the difference between “loose” or 50 Hz to 60 Hz vibrating components such as a transformer winding and the actual electrical discharges.



Key

1 transducer preamp
2 variable gain amplifier
3 demodulation circuit
4 mixer
5 oscillator
6 low pass filter
7 audio amplifier
8 phone output
9 line output
10 RMS to DC converter
11 digital I/O
12 sensitivity/frequency adjustment knob
13 store button
14 CPU and digital controls
15 gain control
16 frequency control
17 converter input
18 display

Figure 1 — Block diagram example of an ultrasonic detector

8 Data collection guidelines

8.1 General

Several techniques are recognized and in use throughout industry to collect data. With the most recent advances, ultrasonic detectors have become much more sophisticated and have evolved from subjective listening devices with hand-written data, to systems that can store test data, record sound samples, and analyse the data through data management software and the recorded sound samples with spectral analysis software. This provides the capability to identify changes in condition of monitored equipment and to determine any further action to be taken.

Each of these ultrasound techniques can be used as part of a condition-monitoring process when such a process is implemented in accordance with ISO 17359[4]. Ultrasound can also be used as a primary or secondary technique for diagnosis and prognosis when these processes are carried out in accordance with ISO 13379-1[2] and ISO 13381-1[3], respectively.

8.2 Comparative ultrasound

When starting an inspection route for the first time, it is important to be able to identify anomalies, especially those that can be in a failure state. The most common technique is to use the comparative method. It is the best method to use when there are no established baselines set and a series of points on a machine needs to be assessed with no previous assessment criteria. As with all technologies, the confidence level of the information obtained is dependent on the equipment used, training and experience of the inspector and detection method applied.

Comparative ultrasound can be either *quantitative* or *qualitative*. The quantitative method is the most often used method for many ultrasound applications. This method uses the strength of the signal, expressed in decibels, (commonly called “decibel value”) to determine the severity of a component's condition. The resultant decibel value is compared to that of similar component or equipment baseline.

Many applications do not require quantitative data to monitor the condition of components of a machine. In the case of compressed air leaks and electrical discharges, qualitative techniques are usually the preferred methods, as these conditions do not produce ultrasound if they do not exist.

A typical example of the qualitative technique is where there are multiple electrical components operating at the same voltage under the same load and where one component is discharging, producing an ultrasonic signal. This is usually an indication of a deteriorating condition. In this instance, an evaluation of the demodulated or heterodyned sound pattern would be a better indicator of severity than change in signal level (decibel value). The sound analysis provides information that identifies the type and severity of the condition. This is where qualitative measurements can help locate the source of the emission by the increase in the signal level and the sound quality indicates the degree of severity.

Each application would require a plant or an individual to establish their own set of criteria for degradation levels. As an example, a compressed air leak that has an extremely low decibel value may not require repair, while a larger leak with a high decibel value would require repair. A detectable air leak at 1×10^{-2} cm^3/s may not justify repair, while a leak at 100 cm^3/s would.

8.3 Baseline method — Quantitative ultrasound

The most common structure-borne ultrasound method in use for condition monitoring is the baseline or quantitative method. This is important when critical plant components are monitored on a routine basis for diagnostic reference. When subsequent inspections or surveys indicate an increase in the decibel value or a change in sound characteristics, these baselines can be used for a comparison. This is useful to identify deteriorating conditions before they require any major maintenance or become catastrophic. The baseline method can include decibel value and baseline sound samples. The advantage of a baseline sound sample is the ability to review and analyse any changes in the subject equipment based on spectral and or time series views that might not be apparent with just a decibel value.

8.4 Data collection

Data collection should be conducted in accordance with the following guidelines.

— The ultrasound inspector should have adequate knowledge of the components, construction and theory of machines to detect a fault condition or anomaly (examples in Table 2).

— The ultrasound inspector should use ultrasound instruments with capabilities sufficient to meet the inspection requirements specified in Clause 7.

— Data may be stored via data logging on the ultrasound instrument and downloaded to appropriate software or hand written and logged into an appropriate record.

— Data should include all relevant information to allow for repeatable, reliable reporting such as, but not limited to, date and time, description of test object, description and location of indication, decibel amplitude level and recommendation.

— A component that is repaired or replaced should be reinspected to assure that the machine has returned to normal operating condition.

Table 2 — Typical fault types and assessment criteria

Machine description	Fault type	Assessment criteria	
		Change in signal strength (decibel value)	Signal analysis
Heat exchangers	Leak	×	—
Boilers	Leak	×	—
Condensers	Leak	×	—
Control air systems	Leak	×	—
Pressurized gas systems	Leak	×	—
Valves	Leak	×	×
Steam traps	Leak	×	×
Motors	Mechanical or electrical failure, or both	×	×
Pumps	Mechanical failure leaks, cavitation	×	×
Gears/gear boxes	Mechanical failure	×	×
Fans	Mechanical failure	×	×
Compressors	Mechanical failure	×	×
Conveyors	Mechanical failure	×	×
Switchgear	Electrical discharge, mechanical failure	×	×
Transformers	Electrical discharge, mechanical failure, leaks	×	×
Insulators	Electrical discharge	×	×
Junction boxes	Electrical discharge	×	×
Circuit breaker	Electrical discharge, leaks	×	×
Turbines	Mechanical failure, leaks	—	×
Generators (utility)	Mechanical failure, electrical discharge, leaks	×	×
Lubrication	Mechanical failure	×	×
High-speed bearings	Mechanical failure	×	×
Low-speed bearings	Mechanical failure	×	×

8.5 Assessment criteria

The most common form of severity criterion is the use of a signal level differential (delta dB).

To apply ultrasound inspection to the condition monitoring of machines and their components, severity criteria should be established by the practitioner, their company or client. It is common practice that these criteria are established through experience and the accumulation of data on specific machines or components. Since there are many applications of ultrasound that differ in the way data are evaluated, there are currently no universally accepted severity criteria in industry. Therefore, each category of equipment and its application should have severity criteria established based on its design, operating conditions, baseline condition, maintenance, and criticality.

These severity criteria are usually based on historical data showing an increase in decibel value (quantitative baseline method). This can help establish a rate of deterioration and help establish when corrective action is taken to prolong component life. This can apply to applications that would use a decibel value increase as a criterion, such as on bearing lubrication levels where the corrective action would be to lubricate the bearing to reduce the ultrasonic decibel value. Other examples of severity criteria are: elevated ultrasonic signals along with information from spectral analysis of electrical components which could cause machinery shutdown and decibel value increases in compressed air system leaks, which could cause machine performance degradation, or high energy costs.

As multiple measurements are taken over time on the same piece of equipment under the same operating conditions, the recorded data can be used to set parameters for trending and aid in the prediction of the failure of these components.

An example of severity criteria based on increased decibel value above an established reference or baseline for rotating equipment bearings is as follows:

— *Pre-failure stage — 8 dB*: This is the earliest stage of failure. The bearings may have developed hairline cracks or microscopic spots that are not visible to the human eye. This may also signal a need to lubricate the bearing.

— *Failure stage — 16 dB*: At this stage, visible flaws develop along with a marked rise in acoustic energy and the temperature of the bearing begins to rise. It is at this stage that the bearings should be replaced or more frequent monitoring should occur.

— *Catastrophic stage — catastrophic failure — 35 dB to 50 dB*: Here, rapid failure is imminent. The acoustic sound level is so intense as to be audible and the temperature of the bearings has risen enough to cause overheating. This is a highly dangerous stage since changes in the bearing clearances and tolerances can cause additional friction and rubbing within the machine, potentially damaging other components.

9 Sensitivity validation guidelines

Ultrasound inspectors shall verify the sensitivity of their instruments on a regular basis and shall have them calibrated to the manufacturer's specifications. One common sensitivity validation method is described in ASTM E1002[7] where a calibrated reference ultrasonic source is used. It is recommended that a sensitivity validation procedure be performed prior to each inspection or survey. A quick sensitivity check can be made by using the detection of a human eye blink as a low level signal for airborne sensors and the detection of the signal from a quartz watch crystal in a wristwatch for structure-borne sensors.

10 Monitoring interval

Monitoring intervals can be established based on severity criteria such as the expected rise in decibel value over time that is representative of a fault condition or an ultrasonic pattern anomaly. Examples of monitoring interval schedules are as follows:

— *Monthly* — If the loss of a component or system would shut down an operation;

— *Every other month* — If there is a back-up component or system in case one component or system fails;

— *Quarterly* — If the operation could continue to operate without the component or system if it were to fail.

11 Data interpretations

When the ultrasound instrument detects deviations from baseline or previous readings, these variations should be noted; the decibel value data and demodulated or heterodyned ultrasound anomalies should be recorded and analysed for severity and subsequent corrective actions. The use of spectrum and time series analysis is very helpful not only to determine the severity of the anomaly, but also to provide a way of reporting the condition of the item under evaluation as a "sound image". Examples of typical fault types and assessment criteria are shown in Table 2.

If the initial evaluation of the anomaly is not conclusive, further action is required, such as the evaluation of the anomaly with alternate methods suitable for the diagnosis and subsequent corrective action. These technologies could be acoustic emission, infrared imaging, vibration analysis, motor current analysis, and oil analysis.

12 Reporting

Reporting of the ultrasound data can be in the form of either a graph or chart to show the trend of the decibel value increase over time for those applications where trending is appropriate. Those applications that are qualitative, and where a change in decibel value is not indicative of a failure, can be reported as an image of the spectrum or time series, or both, of a recorded audio file of the anomaly. Typical examples are shown in Annex B.

Annex A
(informative)

Example of a compressed air leak survey

A.1 Compressed air procedure

In order to create a successful compressed air leak survey, there should be a planned, organized approach. The first thing to consider is what is to be accomplished with the survey. Is it going to be a one-time investment or a part of an ongoing programme? Is the goal of the survey to reduce energy costs or improve production or both?

If the goal is to introduce an ongoing programme, it is necessary to set up a workable schedule. This can vary from once a month to once a year. Often an audit or compressed air review is used to determine whether there is a need for additional compressed air equipment. The audit can help to determine whether the use of compressed air has increased due to expanded production or equipment requirements, or if it has increased because of air loss.

Other considerations are: alternative utilities available to perform the task (e.g. when electric controllers can be used in place of compressed air), what types of compressors are being used, and compressors with variable speed drives. Also are there alternative compressor types that can be more economical?

Of considerable importance is to consider what is to be done to educate employees about the effective use of compressed air. They need to know that wasted air is not free; it affects everybody. When waste hits the bottom line, it has an impact on the profitability of a company.

Before beginning the survey, create a plan. Here are some suggestions.

a) Limit the leak test area to a manageable size. Do not be overly ambitious. Walk the plant section by section to determine the strategy to consider where the survey starts and plan the route. It is recommended the survey be started at the compressor area and move out from there.

b) Walk through the plant section by section.

   1) Pay attention to and note air-waste practices.

   2) Note the location of obvious leaks.

   3) Note potential safety hazards.

   4) Determine what equipment is needed such as flashlights, ladders, etc.

c) Select the inspection equipment. Are specialized modules needed, e.g. a parabolic microphone for high or hard-to-reach areas, or is the standard scanner sufficient?

d) Set up a leak identification or tag system. Use tags and hangers that can be placed on leaks. The tags should have numbers or codes that are used in the record keeping.

e) Consider how to report the results. Take a digital photograph of the leaks with the tags attached. If it is required to report cost savings, perform a cost analysis using software which produces the cost justification for repairs.

f) Be sure to install a system of leak reporting and follow-up to be sure the leaks are repaired. When the survey is completed and the repairs are finished, retest to be sure the leaks have been repaired properly and that no new leaks were created during the repair.

g) If leaks have been present for a long time before the survey, it is likely that the pressure in various parts of the plant has been increased over time. Recheck those areas and bring the pressure down to the appropriate level.

A.2 Instrument set-up

a) Analogue:

   1) plug in headphone;

   2) check batteries and replace, if necessary;

   3) perform sensitivity validation;

   4) set instrument to peak frequency response.

b) Digital:

   1) be sure the memory is cleared and is sufficient for the survey;

   2) perform sensitivity validation;

   3) set frequency to the peak response of the ultrasonic instrument;

   4) check battery level.

A.3 Test materials

a) Suggested materials to bring:

   1) writing pad and pen/clipboard;

   2) flashlight;

   3) wipe rag;

   4) tags and hangers;

   5) marker pen;

   6) digital camera.

b) Suggested accessories:

   1) parabolic microphone;

   2) rubber focusing probe.

A.4 Inspection

a) Safety:

1) be aware of and observe all safety procedures;

2) wear appropriate clothing and other protective gear, as required;

3) follow all confined space procedures when entering such conditions.

b) Pre-inspection:

1) walk the test area, use piping diagram or take digital photos of piping and components — if using a digital camera, take long-range and close-up photos;

2) during walk-through:

i) plan the scan strategies,

ii) note air wasting activities such as abuse, open valves, etc.,

iii) note and tag obvious leaks,

iv) take a note of any additional items which may be needed for an efficient test such as a hi-low or ladder, keys to open locked cabinets (observe lockout-tag out procedures, if called for).

c) Test procedure:

1) test one area at a time in the planned route;

2) use shielding methods when confronted with competing ultrasounds;

3) confirm the leak location by:

i) scanning around the suspect leak area in all directions (360°),

ii) sealing the rubber focusing probe against the leak area.

d) Tag the leak.

e) Take digital photos of the leak with a tag.

f) Perform compressed air loss analysis.

g) Enter data into an electronic report.

h) Create work order and attach photo (close-up of leak site) to work order.

A.5 Post inspection

a) Verify that the repairs have been completed.

b) Retest repaired leaks.

c) Update report with repaired leaks entered.

d) Issue report showing:

   1) number of leaks found;

   2) number of leaks repaired.

e) Compressed air loss or compressed air saved.

f) Economic savings potential determined by the survey — if a before and after log of compressor run time is taken, a good assessment of economic gains can be obtained from the survey.

g) Recommendations.

h) Schedule future surveys.