INTERNATIONAL STANDARD

ISO 13373-2

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Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 2: Processing, analysis and presentation of vibration data

Surveillance des conditions et diagnostic des machines — Surveillance relative aux conditions des vibrations —

Partie 2: Traitement, analyse et présentation des données vibratoires

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13373-2 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

ISO 13373 consists of the following parts, under the general title *Condition monitoring and diagnostics of machines — Vibration condition monitoring*:

— *Part 1: General procedures*

— *Part 2: Processing, analysis and presentation of vibration data*

Further parts are under preparation:

— *Part 3: Basic techniques for diagnostics*

Introduction

The purpose of this part of ISO 13373, which covers the area of vibration condition monitoring of machines, is to provide recommended methods and procedures for processing signals and analysing data obtained from vibration transducers attached to a machine at selected locations for the purpose of monitoring the dynamic behaviour of a machine.

Broadband vibration measurements provide an overview of the severity of machine vibration that can be observed and trended to alert machine users when an abnormal condition exists with a machine. Processing and analysing these vibration signals further in accordance with the procedures specified in this part of ISO 13373 gives the user an insight into ways of diagnosing the possible cause or causes of the machinery problems, which allows for more focused continued condition monitoring.

The advantages of such a monitoring programme are that machinery operators will not only be made aware that a machine may fail at a certain time, and that maintenance should be planned prior to the failure, but it will provide valuable information regarding what maintenance should be planned and performed. The vibrations are manifestations or symptoms of problems such as misalignment, unbalance, accelerated wear, flow and lubrication problems.

ISO 13373-1 contains guidelines for vibration condition monitoring of machines. This part of ISO 13373, however, contains guidelines for the processing, presentation and analysis of the vibration data thus obtained, and that can be used for diagnostics to determine the nature or root causes of problems.

The signal processing, analysis and diagnostic procedures applied to vibration condition monitoring may vary depending on the processes to be monitored, degree of accuracy desired, resources available, etc. A well-conceived and implemented condition monitoring programme will include consideration of many factors, such as process priority, criticality and complexity of the system, cost-effectiveness, probability of various failure mechanisms and identification of incipient failure indicators.

An appropriate process analysis needs to dictate the types of data desired to monitor the machinery condition suitably.

The vibration analyst needs to accumulate as much pertinent information as possible about the machine to be monitored. For example, knowing the vibration resonant frequencies and the excitation frequencies from design and analytical information will provide an insight regarding the vibration frequencies anticipated and, consequently, the frequency range that is to be monitored. Also, knowing the machine’s initial condition, the machine’s operational history, and its operating conditions provides additional information for the analyst.

Other advantages to this pre-test planning process are that it provides guidance as to what types of sensors are needed, where they should optimally be located, what kind of signal conditioning equipment is required, what type of analysis would be most appropriate, and what are the relevant criteria.

Further standards on the subject of machinery condition monitoring and diagnostics are in preparation. These are intended to provide guidance on the overall monitoring of the “health” of machines, including factors such as vibration, oil purity, thermography and performance. Basic techniques for diagnostics will be described in an additional part of ISO 13373, which is under preparation at present.

Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 2:
Processing, analysis and presentation of vibration data

1 Scope

This part of ISO 13373 recommends procedures for processing and presenting vibration data and analysing vibration signatures for the purpose of monitoring the vibration condition of rotating machinery, and performing diagnostics as appropriate. Different techniques are described for different applications. Signal enhancement techniques and analysis methods used for the investigation of particular machine dynamic phenomena are included. Many of these techniques can be applied to other machine types, including reciprocating machines. Example formats for the parameters that are commonly plotted for evaluation and diagnostic purposes are also given.

This part of ISO 13373 is divided essentially into two basic approaches when analysing vibration signals: the time domain and the frequency domain. Some approaches to the refinement of diagnostic results, by changing the operational conditions, are also covered.

This part of ISO 13373 includes only the most commonly used techniques for the vibration condition monitoring, analysis and diagnostics of machines. There are many other techniques used to determine the behaviour of machines that apply to more in-depth vibration analysis and diagnostic investigations beyond the normal follow-on to machinery condition monitoring. A detailed description of these techniques is beyond the scope of this part of ISO 13373, but some of these more advanced special purpose techniques are listed in Clause 5 for additional information.

For specific machine types and sizes, the ISO 7919 and ISO 10816 series provide guidance for the application of broadband vibration magnitudes for condition monitoring, and other documents such as VDI 3839 and VDI 3841 provide additional information about machinery-specific problems that can be detected when conducting vibration diagnostics.

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.

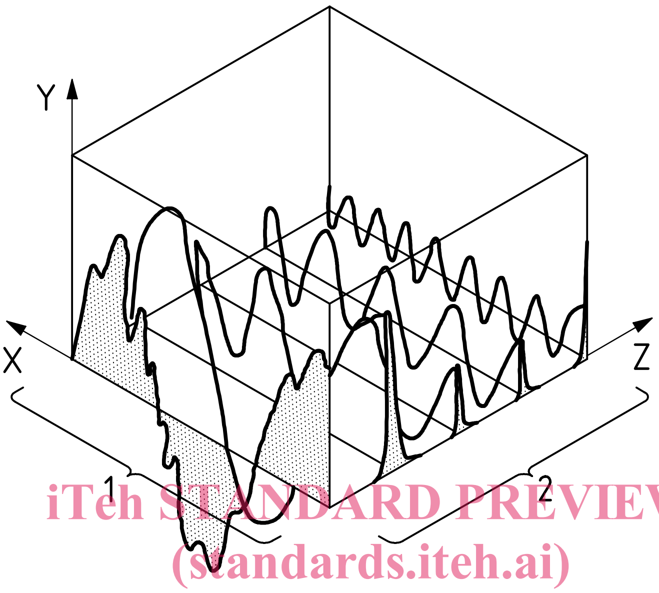
ISO 1683, *Acoustics — Preferred reference quantities for acoustic levels*

3 Signal conditioning

3.1 General

Virtually all vibration measurements are obtained using a transducer that produces an analog electrical signal that is proportional to the instantaneous value of the vibratory acceleration, velocity or displacement. This signal can be recorded on a dynamic system analyser, investigated for later analysis or displayed, for example, on an oscilloscope. To obtain the actual vibration magnitudes, the output voltage is multiplied by a calibration factor that accounts for the transducer sensitivity and the amplifier and recorder gains. Most vibration analysis is carried out in the frequency domain, but there are also useful tools involving the time history of the vibration.

Figure 1 shows the relationship between the vibration signal in the time and frequency domains. In this display, it can be noted that there are four overlapping signals that combine to make up the composite trace as it would be seen on the analyser screen (black trace). Through the Fourier process, the analyser converts this composite signal into the four distinct frequency components shown.



Key

X time

Y amplitude/magnitude

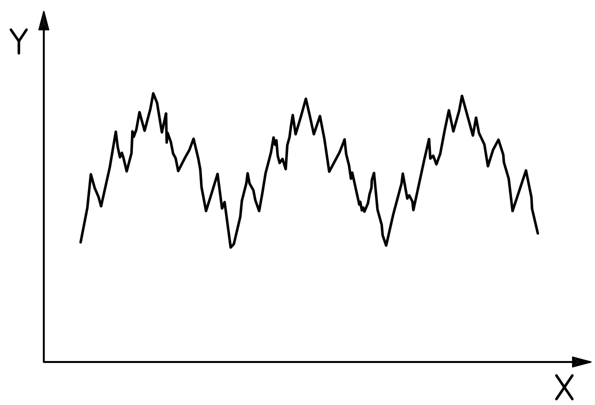
Z frequency

1 time domain oscillogram

2 frequency domain spectrum

Figure 1 — Time and frequency domains

Figure 2 is a simpler example of a composite trace from a single transducer as seen on the analyser screen. In this case, there are only three overlapping signals, as shown in Figure 3, and their distinct frequencies are included in Figure 4.

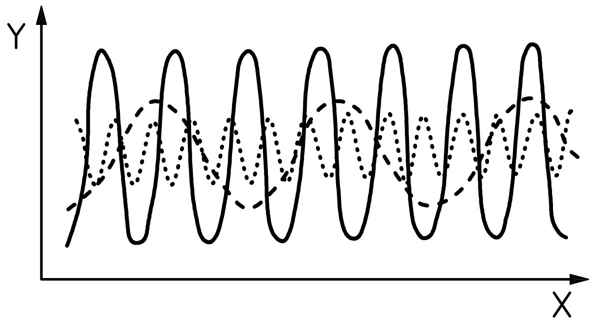


Key

X time

Y amplitude

Figure 2 — Basic spectra composite signal



Key

X time

Y amplitude

Figure 3 — Overlapping signals

Key

X frequency

Y amplitude

Figure 4 — Distinct frequencies

For many investigations, the relationship between vibration on different structure points, or different vibration directions, is as important as the individual vibration data themselves. For this reason, multi-channel signal analysers are available with built-in dual-channel analysis features. When examining signals with this technique, both the amplitude and phase relationships of the vibration signals are important.

3.2 Analog and digital systems

3.2.1 General

The analog signal from a transducer can be processed using analog or digital systems. Traditionally, analog systems were used that involved filters, amplifiers, recorders, integrators and other components which modify the signal, but do not change its analog character. More recently, the advantages of digitizing the signals have become more and more apparent. An analog-to-digital converter (ADC) repeatedly samples the analog signal and converts it to a series of numerical values. Mathematical routines on computers can then be used to filter, integrate, find spectra (see 4.3.2), develop histograms or do whatever is required. Of course, the digitized signal may also be plotted as a function of time. The analog signal, as well as the digitized one, contains the same information on the premises of an appropriate choice of the sampling frequency.

When using either an analog method or a digital method, it is important to know the sensitivity of the signal to be measured. The sensitivity is the ratio of the actual output voltage value of the signal to the actual magnitude of the parameter measured. To obtain adequate signal definition, the signal of interest should be significantly greater than the ambient noise levels, but not so large that the signal is distorted (e.g. so that the peaks of the signal are clipped).

3.2.2 Digitizing techniques

The most important parameters in the digitizing process are the sampling rate and the resolution. It is important to ensure that no frequencies are present above half the sampling rate. Otherwise, time histories will be distorted or fast Fourier transforms (FFT) will show aliasing components that do not really exist (see 4.3.7 for further information about aliasing). The sampling rate will be determined by the type of analysis to be performed, and the anticipated frequency content of the signal. If a plot of vibration versus time is desired, it is recommended that the sampling rate be of about 10 times the highest frequency of interest in the signal. However, if a frequency spectrum is desired, an FFT calculation requires that the sampling rate needs to be greater than 2 times the highest frequency of interest to be measured. Anti-aliasing filters are used to eliminate any high-frequency noise or other high-frequency components that are above half the sampling rate. When digitizing, the number of bits used to represent each sample shall be sufficient to provide the required accuracy.

3.3 Signal conditioners

3.3.1 General

The vibration signals from transducers usually require some sort of signal conditioning before they are recorded in order to obtain proper voltage levels for recording, or to eliminate noise or other unwanted components. Signal conditioning equipment includes transducer power supplies, pre-amplifiers, amplifiers, integrators and many types of filters. Filtering is discussed further in 3.4.

3.3.2 Integration and differentiation

Vibration records can be in terms of displacement, velocity or acceleration. Usually one of the parameters is preferred because of the frequency range of interest (low-frequency signals are more apparent when using displacement, and high-frequency signals are more apparent when using acceleration) or because of the applicable criteria. A vibration signal may be converted to a different quantity by means of integration or differentiation. Integrating acceleration with respect to time gives velocity, and integrating velocity gives displacement. Double integration of acceleration will produce displacement directly. Differentiation does the opposite of integration.

Mathematically, for harmonic motion, the following relationships apply:

displacement: $$x = \int v \, \mathrm{d}t = \iint (a \, \mathrm{d}t) \, \mathrm{d}t = -1/\omega^2 \, a \qquad (1)$$

velocity: $$v = \frac{\mathrm{d}x}{\mathrm{d}t} = \int a \, \mathrm{d}t \qquad (2)$$

acceleration: $$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} \qquad (3)$$

where ω is the angular frequency of the harmonic vibration with $\omega = 2\pi f$.

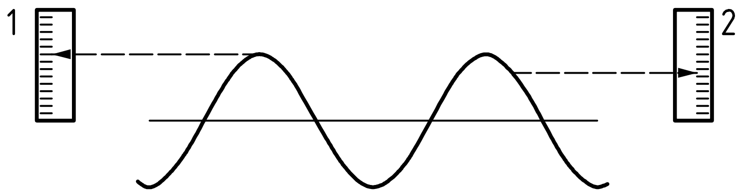
NOTE See also 4.3.12.

A common vibration transducer is the accelerometer, so integration is much more common than differentiation. This is fortunate since differentiation of a signal is more difficult than integration, but special care shall be taken when integrating signals at low frequencies. A high-pass filter should be used to eliminate frequencies lower than those of interest before integrating.

3.3.3 Root-mean-square vibration value

The root-mean-square (r.m.s.) value of the vibration signal is commonly used in vibration evaluation standards. Criteria often apply to r.m.s. vibration values within a certain frequency range. This is the most used quantity of vibration over a given time period. Other measures of a vibration signal can be confusing when there are many frequency components, or when there is modulation, etc. However, the r.m.s. value is a mathematical quantity that can be found for any signal, and most instruments are designed to find that quantity (see Figure 5). Alternatively, the r.m.s. value may be found by using a spectrum analyser, by integrating the spectrum between the upper and lower frequencies of interest.

A vibration signal may be filtered as required and displayed on an r.m.s. meter if the reading does not change significantly in a short time period. However, if the indicated output varies significantly, an average over a certain period of time shall be obtained. This may be done with an instrument that has a longer time constant.



a) Sinusoidal signal where the r.m.s. value equals 0,707 times the peak value

b) Non-sinusoidal signal

Key

1 peak value

2 r.m.s. value

Figure 5 — R.m.s. value

3.3.4 Dynamic range

The dynamic range is the ratio between the largest and smallest magnitude signals that a particular analyser can accommodate simultaneously. The magnitudes of the signals are proportional to the output voltages of the transducers, usually in millivolts.

The dynamic range in analog systems is usually limited by electrical noise. This is usually not a concern with respect to the transducer itself, but filters, amplifiers, recorders, etc., all add to the noise level, and the result may be surprisingly high.

In digital systems, the dynamic range is dependent on the sampling accuracy, and the sampling rate shall be adequate for the frequencies of concern. The relationship between the number of bits, N, used to sample an analog signal and the dynamic range D (if one bit is used for the sign) is as follows:

$$6\,(N-1) = D \text{ dB} \qquad (4)$$

Therefore, a dynamic signal analyser (DSA) with 16 bits of resolution will have a dynamic range of 90 dB, but any inaccuracies will reduce the dynamic range.

3.3.5 Calibration

The calibration of individual transducers is well covered in the referenced documents (e.g. ISO 16063-21), and is usually carried out in the laboratory before their use *in situ*. It is recommended, however, that a calibration check be carried out for any field installation. The field calibration check normally does not include the calibration of the transducer, but does include the rest of the measuring/recording system, such as amplifiers, filters, integrators and recorders. Most often it involves the insertion of a known signal into the system to see what output relates to it. The signal may be a d.c. step, a sinusoid or random noise, depending on the type of measurement.

Certain transducers, such as displacement transducers or proximity probes, are precalibrated. However, in this case, their calibrations should be checked in the field in conjunction with the surface being measured, since proximity probes are sensitive to shaft metallurgy and finish. Calibration of these probes is carried out in place with micrometre spindles, and the outputs for each are noted.

When checking the calibration of seismic transducers in the field, a shake table is required.

Strain gauges are also often calibrated in the field after they are installed. The most desirable calibration is for a known load to be applied to the component being measured. If that is not practical, a shunt calibration may be made where a calibration resistor is connected in parallel with the strain gauge, thus changing the apparent resistance of the gauge by a known amount, which is equivalent to a certain strain determined by the gauge factor.

3.4 Filtering

There are three basic types of filters available for signal conditioning and analysis:

— low pass,

— high pass, and

— bandpass.

Low-pass filters, as the name implies, are transparent only for the low-frequency components of the signal, and they block out the high-frequency components above the filter limiting frequency (cut-off frequency). Examples of application are anti-aliasing filters (see 4.3.7), or filters that exclude high-frequency components that are unwanted for special investigations (e.g. gear meshing components for balancing).

High-pass filters are mainly used to exclude low-frequency transducer noise (thermal noise), or some other unwanted components from the signal, prior to analysis. This can be important since such components, although of no interest, can dramatically reduce the useful dynamic range of the measurement equipment.

Bandpass filters, when included for analysis, are used to isolate distinct frequency bands. Very common bandpass filter types are the octave filters or $1/n$ octave filters, which are especially used to correlate vibration measurements with noise measurements.

Filtering is particularly important when analysing signals with large dynamic ranges. If there are frequencies in the spectra with both high and low amplitudes, for instance, they cannot usually be analysed with the same level of accuracy because of limitations in the dynamic range of the analyser. In such cases, it may be necessary to filter out the high-amplitude components to examine more closely those of low amplitude.

Filtering is also important for separation of informative signals and disturbances (as electronic noise is in the high-frequency range or seismic waves are in a very low-frequency range).

When filters are used to isolate a particular frequency component to examine the waveform, care shall be taken to ensure that the filter sufficiently excludes any component of frequencies other than those of interest. Simple filters, analog as well as digital, do not have very sharp cut-off characteristics, because the filter slope outside of the transmission band is poor.

EXAMPLE A particular filter with a 24 dB per octave slope will pass about 15 % of a component with twice the frequency, and about 45 % of a component with 1,5 times the cut-off frequency. To improve the filter's suppression characteristics, several simple filters can be cascaded, or a higher-order filter can be used instead.

4 Data processing and analysis

4.1 General

Data processing consists of raw-data acquisition, filtering out unwanted noise and/or other non-related signals, and formatting the measured signals in the form required for further diagnosis. Therefore, data processing is an important step towards achieving a fruitful and meaningful diagnosis. The device that acquires the vibration signals from the transducer should have adequate resolution in both amplitude and time. If digital data acquisition is utilized, then the amplitude resolution should be high enough for the application. A higher number of bits of resolution provide the ability to obtain greater accuracy and sensitivity, but it typically requires more expensive hardware and greater processing power.

Once the signals are acquired, the next step is to process them and then display the outputs in various useful formats so that the diagnosis is made much easier for the user. Examples of such formats include Nyquist plots, polar plots, Campbell diagrams, cascade and waterfall plots and amplitude decay plots. The objective of this clause, therefore, is to present these various methods of presentation available to the user in order to determine better the conditions of machines.

4.2 Time domain analysis

4.2.1 Time wave forms

In the past, waveform analysis was the primary method of vibration analysis. An instantaneous vibration versus time strip chart or oscillograph was usually analysed graphically, and broadband peaks were noted. While these broadband techniques are still being used, it is helpful to look at the waveform with some of the more basic techniques in mind. For example, a scratched journal can be detected by looking at waveform data from displacement transducers, a waveform with a clipped top or bottom can indicate a rub, mechanical looseness, etc.

While these time-domain signatures can portray waveforms that provide basic information regarding the nature of a phenomenon occurring in a machine, the more in-depth frequency analysis techniques described in 4.3 may be required.

The analysis of waveforms is based on the principle that any periodic record may be represented as a superposition of sinusoids having frequencies that are integral multiples of the frequency of the waveform. Figures 6 to 9 show several examples of waveforms.

Figure 6 is essentially a one-cycle sinusoid with a constant amplitude. The double amplitude (or peak-to-peak) of the vibration is obtained by measuring the double amplitude of the trace, and multiplying by the sensitivity of the measuring and recording system, which is found by calibration. The frequency is found by counting the number of cycles in a known time period. The time on an oscillograph is indicated by timing lines, or simply by knowing the paper speed. For the trace shown, there are 60 timing lines per second; therefore, the 12 lines indicate that the fundamental period, T, is 0,2 s, and hence the frequency, $f = 1/T$, is 5 Hz. Accuracy is improved if the number of cycles in a longer section of the record is used.

Figure 7 is the superposition of two sinusoids with three cycles of the lowest frequency shown. The components can be separated by drawing sinusoidal envelopes (upper and lower limits) through all the peaks and troughs as shown. The amplitude and frequency of the low-frequency component is that of the resulting envelope. The vertical distance between envelopes indicates the peak-to-peak value of the high-frequency component, and the high frequency can usually be counted. In this example, it can be found that the frequencies differ by a factor of three. When the frequency ratio of two superimposed sinusoids is high, they may be separated as shown; in all other cases a Fourier analysis is more useful.

