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Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 2: Processing, analysis and presentation of vibration data

Surveillance et diagnostic d'état des machines — Surveillance des vibrations —

Partie 2: Traitement, analyse et présentation des données vibratoires

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Contents

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

This second edition cancels and replaces the first edition (ISO 13373-2:2005), which has been editorially revised.

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*

— *Part 3: Guidelines for vibration diagnosis*

— *Part 9: Diagnostic techniques for electric motors*

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 analyzing 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 analyzing 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 can fail at a certain time, and that maintenance needs to be planned prior to the failure, but that it will provide valuable information regarding what maintenance needs to 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, analysis and presentation 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 can 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 resonance 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 transducers are necessary, where they need to be optimally 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 diagnosis are described in ISO 13373-3.

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 analyzing 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 provide additional information about machinery-specific problems that can be detected when conducting vibration diagnostics.

2 Normative references

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

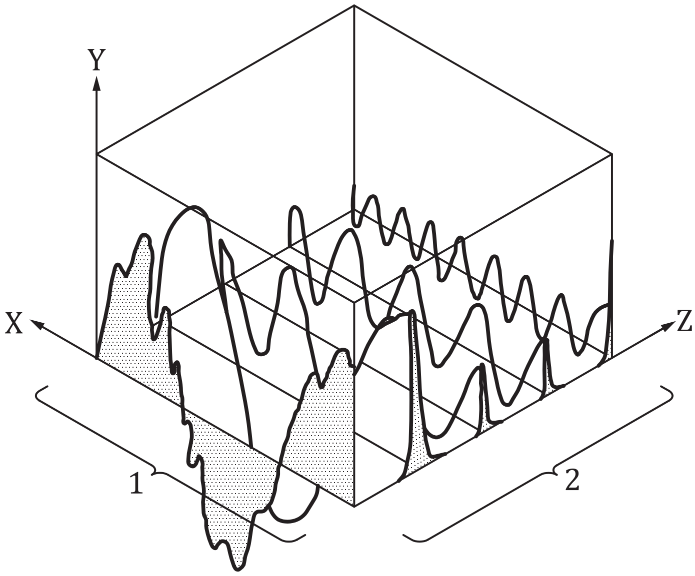
ISO 1683, *Acoustics — Preferred reference values for acoustical and vibratory levels*

3 Signal conditioning

3.1 General

Virtually, all vibration measurements are obtained using a transducer that produces an analogue 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 analyzer, 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 analyzer screen (grey trace in the XY plane). Through the Fourier process, the analyzer converts this composite signal into the four distinct frequency components shown.



Key

X time

Y amplitude/magnitude

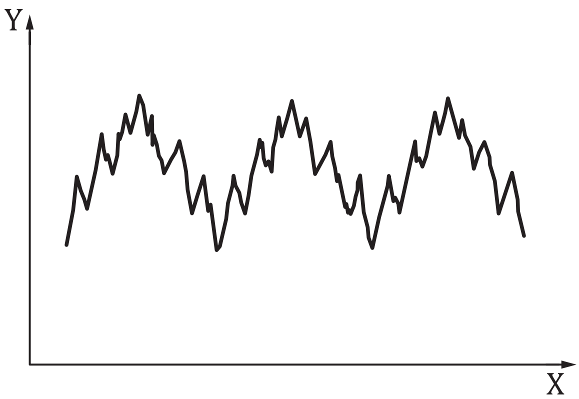
Z frequency

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 analyzer screen. In this case, there are only three overlapping signals, as shown in Figure 3, and their distinct frequencies are included in Figure 4.

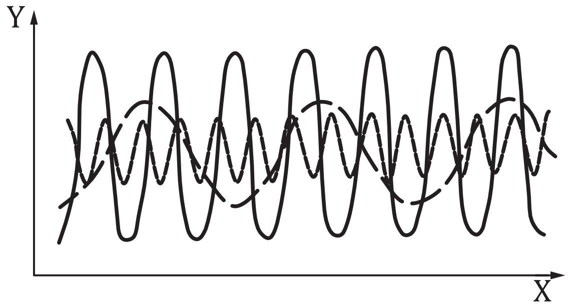


Key

X time

Y amplitude

Figure 2 — Basic spectra composite signal

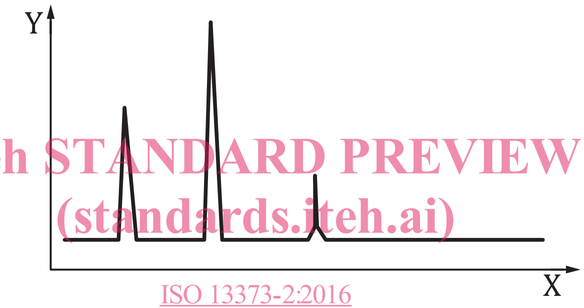


Key

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 analyzers 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 Analogue and digital systems

3.2.1 General

The analogue signal from a transducer can be processed using analogue or digital systems. Traditionally, analogue systems were used that involved filters, amplifiers, recorders, integrators and other components which modify the signal, but do not change its analogue character. More recently, the advantages of digitizing the signals have become more and more apparent. An analogue-to-digital converter (ADC) repeatedly samples the analogue 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 analogue 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 analogue 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 two 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 can 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:

$$x = \int v\mathrm{d}t = \iint \left(a\mathrm{d}t\right)\mathrm{d}t = -\frac{\mathrm{i}}{\omega}v = -\frac{1}{\omega^2}a \tag{1}$$

velocity:

$$v = \frac{\mathrm{d}x}{\mathrm{d}t} = \int a\mathrm{d}t = \mathrm{i}\omega x = -\frac{\mathrm{i}}{\omega}a \tag{2}$$

acceleration:

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\mathrm{d}^2x}{\mathrm{d}t^2} = -\omega^2 x = \mathrm{i}\omega v \tag{3}$$

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

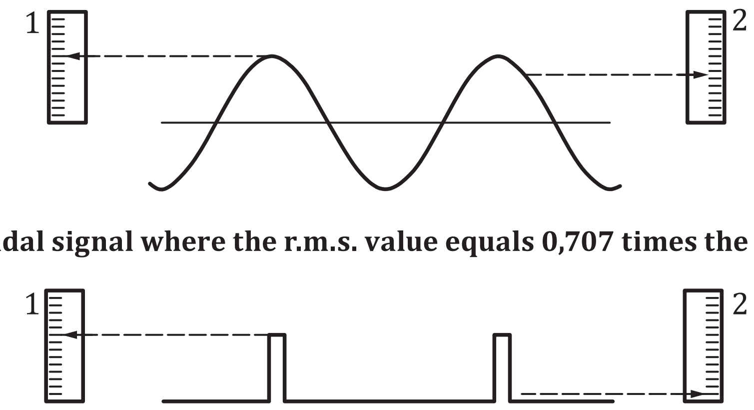
NOTE See also 4.3.12.

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 can be found by using a spectrum analyzer, 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 can 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 — Peak and r.m.s. values

3.3.4 Dynamic range

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

The dynamic range in analogue 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 can 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 analogue signal and the dynamic range D, in decibels, (if one bit is used for the sign) is as follows:

$$6\,(N-1) = D \tag{4}$$

Therefore, a dynamic signal analyzer (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 can 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 pre-calibrated. 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;

— 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 analyzed with the same level of accuracy because of limitations in the dynamic range of the analyzer. In such cases, it can 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, analogue 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

