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Mechanical vibration and shock — Measurement of vibration power flow from machines into connected support structures —

Part 1: Direct method

Vibrations et chocs mécaniques — Mesurage du flux de puissance vibratoire transmis par des machines aux structures de support dont elles sont solidaires — Partie 1: Méthode directe

Reference number
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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 18312-1 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*.

ISO 18312 consists of the following parts, under the general title *Mechanical vibration and shock — Measurement of vibration power flow from machines into connected support structures*:

— *Part 1: Direct method*

— *Part 2: Indirect method*

Mechanical vibration and shock — Measurement of vibration power flow from machines into connected support structures —

Part 1: Direct method

1 Scope

This part of ISO 18312 specifies a method for evaluating the vibration power emitted by machines or pipelines, referred to hereinafter as machines, under operational conditions on to supporting structures to which the machines are directly connected via bolted joints. This part of ISO 18312 specifies the method for evaluating the vibration power components emitted in the six degrees of freedom of a Cartesian coordinate system at each joint, i.e. three translations and three rotations. The vibration power is determined by processing the signals from force and velocity (or acceleration) transducers mounted on to the bolted joints under operational conditions of interest. This method is applicable for machines under the assumption that their vibration can be characterized by a stationary random process.

The components of emitted vibration power in the frequency domain are obtained by computing the cross-spectrum of the force and velocity measurement pairs with a given narrow band width at each bolted joint.

This direct method assumes that the supporting structures are adequately rigid and, hence, it is not applicable to cases where the foundation or supporting structures are resilient, which will potentially go into a state of resonance within the frequency range of interest. Practical frequency limits of the method are specified in this part of ISO 18312.

This part of ISO 18312 can be used in operational conditions for:

a) specification of vibration power emission of machines at the (bolted) joints;

b) identification of vibration power severity;

c) resolving diagnostics issues;

d) planning vibration control measures.

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

ISO 5348, *Mechanical vibration and shock — Mechanical mounting of accelerometers*

3 Terms and definitions

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

3.1
vibration velocity vector
$\boldsymbol{v}^n$
velocity vector at the nth bolt joint, consisting of three translational and three rotational components along the coordinate axes x, y and z

3.2
vibration velocity component
v_i^n
component of the vibration velocity vector in the degree of freedom i at the nth bolted joint; i = 1, 2 and 3 for linear components in the x-, y-, and z-directions, respectively, and i = 4, 5 and 6 for angular components in the x-, y- and z-directions, respectively

3.3
vibration acceleration component
a_i^n
vibration acceleration component in the degree of freedom i at the nth bolted joint

3.4
root mean square value of acceleration component
r.m.s. value of acceleration component
$a_{i:\text{rms}}^n$
root mean square value of the vibration acceleration component in the degree of freedom i at the nth bolted joint

3.5
force vector
$\boldsymbol{F}^n$
vibration force vector at the nth joint, consisting of three components of linear force and three components of angular force, i.e. moment, along the coordinate axes x, y and z

3.6
force component
F_i^n
component of the vibration force vector in the degree of freedom i at the nth joint; i = 1, 2 and 3 for force components in the x-, y- and z-directions, respectively, and i = 4, 5 and 6 for moment components in the x-, y- and z-directions, respectively

3.7
vibration power component
P_i^n
vibration power in the degree of freedom i at the nth bolted joint, equal to the time-averaged scalar product of the vibration force vector and vibration velocity vector in the degree of freedom i at the nth bolted joint

Note to entry: A vibration power component is expressed in watts.

3.8
vibration power at a joint
P^n
vibration power at the nth bolted joint, equal to the sum of the vibration power components in each degree of freedom at that point

3.9
vibration power
P
sum of vibration power of the machine over all joints and in every degree of freedom

3.10
vibration power spectrum
$P(f, \Delta f)$
decomposition of the vibration power of the machine into frequency domain with a given centre frequency, f, narrow frequency band, Δf, equal to the sum of the vibration power spectra over all joints and in every degree of freedom

3.11
component of vibration power spectrum

$P_i^n(f, \Delta f)$

spectrum of the vibration power transmitted in the degree of freedom i at the nth joint

3.12
vibration power spectrum at a joint n

$P^n(f, \Delta f)$

spectrum of the vibration power transmitted at the nth joint

3.13
component of vibration power cross spectrum

$G_{F_i v_i}^n(f)$

cross spectrum of a vibration force component, $F_i(t)$, and a vibration velocity component, $v_i(t)$, in the degree of freedom i at the nth joint

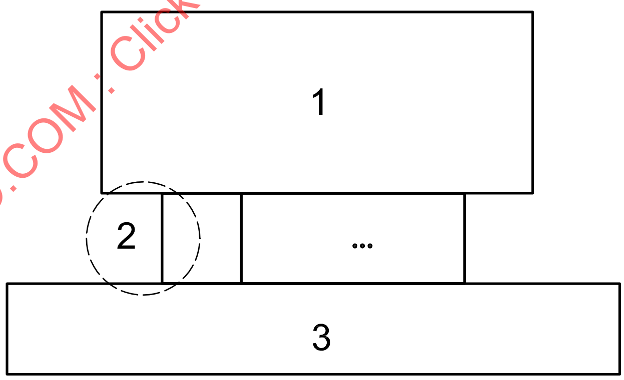
3.14
vibration power level

$$L_W = 10\lg \frac{P}{P_0} \text{ dB}$$

common logarithm of the ratio of measured vibration power to the reference value, P_0 = 1 pW, corresponding to zero level of vibration power

4 Fundamentals

The layout of a machine bolted directly on to the foundation structure at multiple joints is shown in Figure 1 and the detail of a bolted joint is shown in Figure 2 together with a coordinate system, where the z-axis is chosen in parallel with the bolt axis.



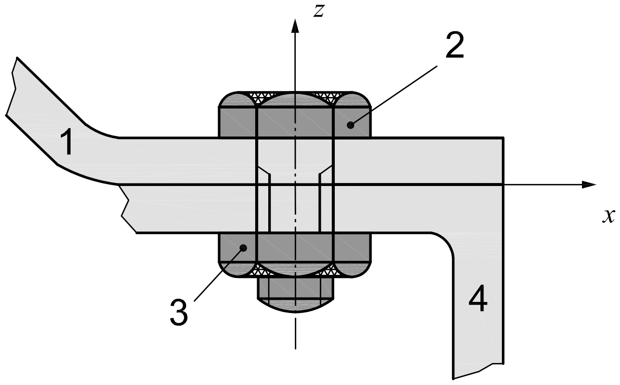
Key

1 machine

2 bolted joints

3 foundation

Figure 1 — Layout of machine bolted on to foundation directly at multiple joints



Key

1 machine leg

2 bolt

3 nut

4 foundation flange

Figure 2 — Coordinate system of a bolted joint

Vibration power emitted by the machine on to the foundation via the nth bolted joint is defined as the time average of scalar product of the force vector and velocity vector as follows:

$$P^n = \frac{1}{L}\int_0^L \boldsymbol{F}^n(t)\cdot\boldsymbol{v}^n(t)\,\mathrm{d}t = \frac{1}{L}\int_0^L \sum_{i=1}^{6} F_i^n(t)\,v_i^n(t)\,\mathrm{d}t = \sum_{i=1}^{6}\frac{1}{L}\int_0^L F_i^n(t)\,v_i^n(t)\,\mathrm{d}t \qquad (1)$$

where the term within the summation on the most right hand side

$$\frac{1}{L}\int_0^L F_i^n(t)\,v_i^n(t)\,\mathrm{d}t \equiv P_i^n$$

denotes vibration power emitted in the degree of freedom i at the nth joint with the index i = 1 to 3 denoting the linear or translational degrees of freedom and the index i = 4 to 6 denoting the angular or rotational degrees of freedom. The record length L in Equation (1) shall be far greater than the fundamental period of the measured signals. In practice, contributions of the rotational components in Equation (1) due to angular velocities and moments may be omitted when difficulty of measurements exists. The total vibration power emitted by a machine with multiple bolted joints on to the support structure can be obtained just by summing up the vibration power transmitted via each bolted joint in Equation (1). Vibration power is a scalar quantity and, hence, the total vibration power emitted from a machine with a number of bolted joints, K, is given simply by a sum:

$$P = \sum_{n=1}^{K} P^n \qquad (2)$$

The vibration power in the ith degree of freedom at the nth joint, P_i^n, can be resolved into the frequency domain by taking real parts of the cross power spectrum $G_{F_i v_i}^n(f,\Delta f)$ from the force signal $F_i^n(t)$ and velocity signal $v_i^n(t)$ using a commercial signal analyser as follows:

$$P_i^n(f,\Delta f) = \mathrm{Re}\left[G_{F_i v_i}^n(f,\Delta f)\right] \qquad (3)$$

where Re[•] denotes the real part of a complex quantity • and the unit of $P_i^n(f,\Delta f) = \mathrm{Re}\left[G_{F_i v_i}^n(f,\Delta f)\right]$ is watt at a centre frequency, f, over a narrow frequency band, Δf, e.g. 1 Hz when the units of the force and velocity are newton and metre per second, respectively. If acceleration $a_i^n(t)$ in metre per second squared is measured instead of the velocity $v_i^n(t)$ in metre per second, the vibration power in Equation (3) is given in a slightly different format as follows:

$$P_i^n(f,\Delta f) = \frac{1}{2\pi f}\mathrm{Im}\left[G_{F_i a_i}^n(f,\Delta f)\right] \tag{4}$$

where Im[•] denotes the imaginary part of the complex quantity •. The sum of the vibration power over frequencies, degrees of freedom, and all the mounts of interest can now be easily calculated. When a partial vibration power over a specific frequency range of interest, in hertz, e.g. from f_{min} to f_{max} is of interest, it can be obtained simply by summing the vibration power spectrum $P_i^n(f,\Delta f)$ in Equation (3) or (4) as follows:

$$P_i^n(f_{\mathrm{min}} \sim f_{\mathrm{max}}) = \sum_{k=1}^{N} P_i^n\left\{\left[f_{\mathrm{min}} + (k-1)\Delta f\right], \Delta f\right\} \tag{5}$$

where N is the number of frequency points over the frequency range of interest given by

$$N = \frac{f_{\mathrm{max}} - f_{\mathrm{min}}}{\Delta f}$$

in case of a narrow frequency band analysis. Once the vibration power spectrum is available in a narrow band from Equations (3) and (4), the vibration power spectrum over one-third octave band or other octave bands can be obtained by simply summing over the bandwidths of interest.

5 Measurement

5.1 General

This part of ISO 18312 specifies how to evaluate the vibration power transmitted by a machine on to its foundation from the measurement of forces and vibration at the bolted joints. Such measurements are not limited to translational degrees of freedom, but may be extended to rotational degrees of freedom, depending upon the capabilities of the employed transducers. This clause explains how to install the vibration and force transducers.

5.2 Arrangement of vibration transducers

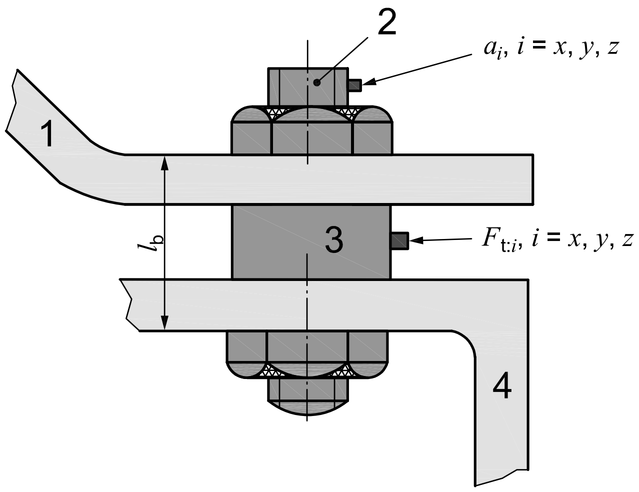
One multi-axial vibration transducer is placed on a joint bolt head as shown in Figures 3 and 4 such that the directions of measurement are aligned with the x- and z-coordinates described in Figure 2. A flat surface on the machine's leg, close to the bolted joint, can also be used if multiple uni-axial transducers are to be placed individually. Details of mounting shall be in accordance with ISO 5348.

5.3 Measurement of forces

5.3.1 General

The forces acting through the bolted joints from the machine on to the foundation can be measured by placing one transducer (see Figure 3) or two transducers (see Figure 4) in the bolted joints. In both cases, this part of ISO 18312 assumes the use of integrated triaxial force transducers.

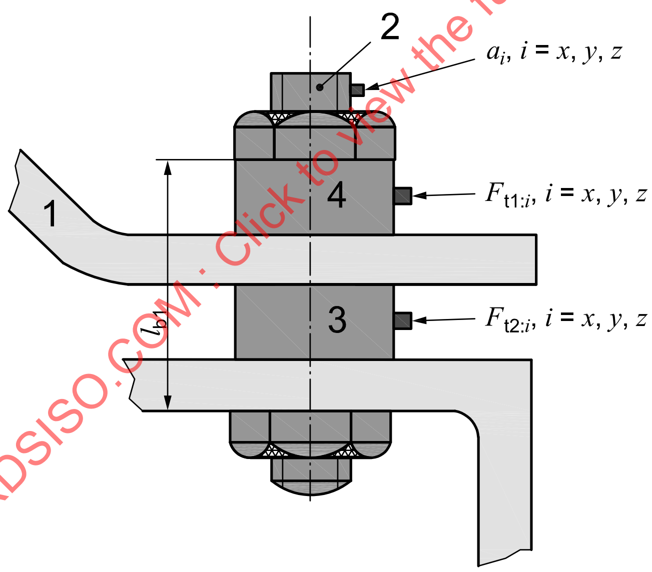
There should be no local resonance near the bolting joint for the method of force measurement by inserting the force transducers at the joint to be effective. A torque wrench should be used to maintain the torque with the force transducers inserted at the value without those.



Key

1	machine leg	a_i	acceleration in the degree of freedom i
2	vibration transducer	$F_{t:i}$	force measured by a transducer in the degree of freedom i
3	force transducer	l_b	length of bolt
4	foundation structure		

Figure 3 — Layout of transducers in one force transducer method



Key

1	machine leg	a_i	acceleration in the degree of freedom i
2	vibration transducer	$F_{t1:i}$	force measured by transducer 1 in the degree of freedom i
3	force transducer 1	$F_{t2:i}$	force measured by transducer 2 in the degree of freedom i
4	force transducer 2	l_{b1}	length of bolt 1

Figure 4 — Layout of transducers in two force transducer method

5.3.2 Measurement of forces by one transducer

One force transducer is mounted into the bolted joint between the machine and the foundation, as shown in Figure 3. In this configuration, the transducer measures only a part of the joint force actually transmitted to the foundation. The other part is transmitted through the bolt itself. Letting F_i and $F_{t:i}$ be the actual transmitted force and the (partial) force measured by the transducer, respectively; they are related to each other as follows:

$$F_i = F_{t:i}\left(1 + \frac{k_{b:i}}{k_{t:i}}\right) \tag{6}$$

where $k_{b:i}$ and $k_{t:i}$ are the stiffnesses of the bolted joint and transducer, respectively, along the axes $i = x, y, z$. The stiffness of force transducers is obtained from their specifications and the stiffness of the bolt joint is calculated as follows:

$$k_{b:x} = \frac{G_b S_b}{l_b} = k_{b:y}; k_{b:z} = \frac{E_b S_b}{l_b} \tag{7}$$

where G_b and E_b are respectively the shear and Young modulus of the bolt material, and S_b and l_b are, respectively, the cross-sectional area and length of the bolt. When the stiffness of the force transducer is very high relative to that of the bolt, which is often the case in practice, $F_i \approx F_{t:i}$.

5.3.3 Measurement of forces by two transducers

In order to avoid possible inaccuracy in calculation of the stiffness of the bolted joint, it is expedient to take another measuring scheme using two force transducers. The layout of force measurement using two force transducers is shown in Figure 4. The first force transducer is located between the machine leg and the foundation to measure $F_{t1:i}$ and the second force transducer is located between the bolt and the machine leg to measure $F_{t2:i}$. Under this configuration, the net force transmitted on to the foundation in the degree of freedom i is the difference of the measurements as follows:

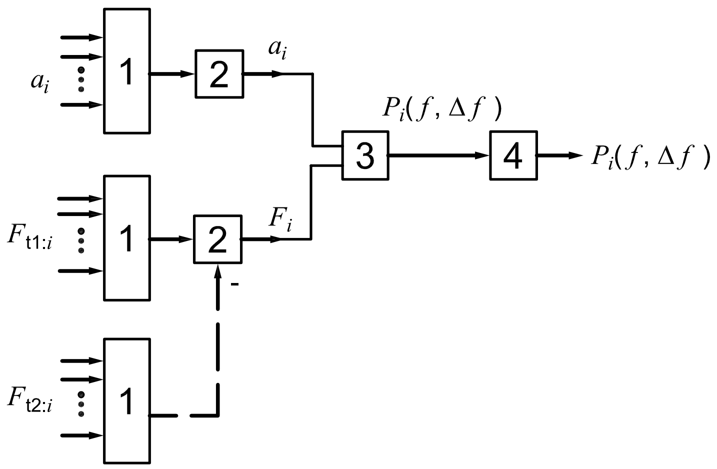
$$F_i = F_{t1:i} - F_{t2:i} \tag{8}$$

5.4 Measurement equipment

A flow chart of a possible measurement to determine the vibration power spectral density function is presented in Figure 5. A multi-channel analyser may also be used.

The subtraction of one signal from the other in the two force transducer method can be performed using an operational amplifier or with the help of digital equipment. Before processing the signals, it is important to check and correct for possible phase differences between channels of accelerometers, force transducers, analogue devices and fast Fourier transform analyser. If the phase shift is less than 0,1°, the correction is not necessary.

One method to correct the phase characteristics between two channels is to apply one wideband signal (e.g. white noise) to both channels and compute the complex transmissibility ratio in narrow frequency band. Usually, a signal analyser has a phase correction program between channels for more accurate cross-spectral density function estimation.



Key

1 channel selector
2 preamplifier
3 two-channel signal analyser
4 computer

a_i acceleration in the degree of freedom i
F_i force transmitted in the degree of freedom i
$F_{t1:i}$ force measured by transducer 1 in the degree of freedom i
$F_{t2:i}$ force measured by transducer 2 in the degree of freedom i
$P_i(f,\Delta f)$ spectrum of the vibration power transmitted in the degree of freedom i

Figure 5 — Typical signal flow chart for estimation of vibration power transmitted via bolted joints

5.5 Metrological specifications

The metrological specifications of the equipment used in measurements of vibration power are shown in Table 1.

Table 1 — Metrological specifications

Measurement equipment	Frequency and voltage range	Accuracy
Dual channel or multi-channel FFT analyser	From 0,5 Hz to 10 000 Hz From 1 μV to 100 V (r.m.s.)	Amplitude ripple: 2 % Phase difference between channels: <0,1°
Signal conditioner	From 0,5 Hz to 10 000 Hz Electric noise level ≤5 μV	Amplitude ripple: 2 % Phase difference between channels: <0,1°
Force transducer	Vary on applications	Calibration uncertainty: <2,5 %
Acceleration transducer	Vary on applications	Calibration uncertainty: <2,5 %

5.6 Determination of upper frequency limit

Rough guidelines for the upper frequency limit, f_{max}, in hertz, of the vibration power measurements are given as follows. In the one force transducer method:

$$f_{max} = \frac{300}{l_b} \tag{9}$$

where l_b, in metres, is the sum of thickness of machine leg, foundation, and forces transducers in the one force transducer method. In the two force transducer method:

$$f_{max} = \frac{300}{l_{b1}} \tag{10}$$

where l_{b1}, in metres, is the sum of thickness of machine leg, foundation, and forces transducers in the two force transducer method. See Figure 3 and Figure 4.

5.7 Choice of number of joints to measure from

In order accurately to obtain the total vibration power emitted by a machine, or identify precisely critical zones of vibration power emission along the machine perimeter, it is preferable to make measurements at all the bolted joints. If this cannot be done in practice, choice of a limited number of bolted joints to measure from can be realized in the following way. While the machine is on, measure the r.m.s. values of the vibration acceleration along the axes $i = x, y, z$, $a_{i:\text{rms}}^n$ from all, say, K mounts:

$$L_i^K = 20 \lg \left[\frac{\sqrt{\sum_{n=1}^{K} (a_{i:\text{rms}}^n)^2 / K}}{a_0} \right] \text{dB} \tag{11}$$

where a_0 is the reference acceleration, 10^{-6} m/s^2, for representation in the decibel scale. Then choose, say, M bolted joints where measurements of vibration power flow are to be performed. The distance between measurements along the sides of the machine should be <1 m, as a rule of thumb.

The root mean square level of vibration acceleration from the M chosen bolted joints is determined using the following formulae:

$$L_i^M = 20 \lg \left[\frac{\sqrt{\sum_{n=1}^{M} (a_{i:\text{rms}}^n)^2 / M}}{a_0} \right] \text{dB} \tag{12}$$

The difference between the root mean square levels from the K and M bolted joints should be <1 dB, i.e.

$$L_i^K - L_i^M \leq 1 \text{ dB} \tag{13}$$

Otherwise, the number of measurement points, M, should be increased closer to the total number of mounts, K.

5.8 Determination of total vibration power by measuring from a limited number of joints

If the vibration power spectrum emitted by a machine is measurable from only M joints, the total vibration power spectrum emitted via all K joints is determined simply using an extrapolation formula:

$$P_i(f, \Delta f) = \frac{K}{M} \sum_{n=1}^{M} P_i^n(f, \Delta f) \tag{14}$$

6 Measurement uncertainty

Uncertainty in the measurements of vibration power flow made according to this part of ISO 18312 is mostly dependent on the ratio of stiffness of the force transducer to that of the machine or the foundation. That is, the higher the ratio, the less the uncertainty. For example, stiffness of a force transducer with a hole of diameter 8 mm is known as 2×10^9 N/m and that of 40 mm as 3×10^{10} N/m although accurate values in practice can be obtained from specifications of the force transducers. It is known from experience that stiffness of main machines and foundations are less than $1{,}25 \times 10^9$ N/m and stiffness of auxiliary machines and foundations are less than $3{,}0 \times 10^8$ N/m. If the ratio of stiffness of the force transducer to that of the machine or the foundation is less than 5, the stiffness of machine or foundation shall be taken into account in the force measurement.

7 Data presentation and test report

The test report should include at least the following information:

a) a reference to this part of ISO 18312 (ISO 18312-1:2012);

b) name of organization which has performed the measurements;

c) measurement date;

d) machine specifications (type, mass, capacity, supports, etc.);

e) description of place, conditions and scheme of testing on the vibration isolators;

f) machine operating modes;

g) vibration noise levels on the test rig;

h) specifications of vibration and force transducers;

i) specifications of measurement equipment, including type, serial number, manufacturer, and calibration characteristics;

j) total vibration power emitted by the machine with the frequency range indicated, total vibration power spectrum with the analysis frequency bandwidth indicated, vibration power spectrum in each of the directions of the concerned motion;

k) total vibration power spectrum with the analysis frequency bandwidth indicated, vibration power spectrum for each bolt (depending on customer's or investigator's request);

l) uncertainty of the results, if any;

m) graphs of vibration power spectrums in a lg(or dB)-lg format as shown in Figure 6 or lg(or dB)-linear format.