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Non-destructive testing — Methods for absolute calibration of acoustic emission transducers by the reciprocity technique

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Non-destructive testing - Methods for absolute calibration of acoustic emission transducers by the reciprocity technique (ISO/TR 13115:2011)

Essais non destructifs - Méthodes d'étalonnage absolu des capteurs d'émission acoustique par la technique de réciprocité (ISO/TR 13115:2011)

Zerstörungsfreie Prüfung - Methode zur Absolutkalibrierung von Schallemissionswandlern durch Reziproktechnik (ISO/TR 13115:2011)

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Foreword

This document (CEN ISO/TR 13115:2011) has been prepared by Technical Committee ISO/TC 135 "Non-destructive testing" in collaboration with Technical Committee CEN/TC 138 “Non-destructive testing” the secretariat of which is held by AFNOR.

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Introduction

A standard method for primary calibration of acoustic emission transducers, ISO 12713:1998[1], introduced the seismic surface pulse method for Rayleigh surface wave calibration, wherein the breaking of a glass capillary is employed for the sound source and a standard capacitive transducer is used for the measurement of dynamic displacements of the surface. In ISO 12714:1999[2], on secondary calibration of acoustic emission sensors, a transducer which has been calibrated by the seismic surface pulse method is employed for comparison of reception sensitivity.

This Technical Report describes the methods for calibrating absolute sensitivity of acoustic emission transducers, both to Rayleigh surface waves and longitudinal waves, by means of a reciprocity technique. Since reciprocity parameters have been derived, absolute sensitivity can be determined by purely electrical measurements without the use of mechanical sound sources or reference transducers.

Procedures of the seismic surface pulse method and reciprocity technique differ from each other; however, there is a common theoretical basis in the two calibration methods. For the seismic surface pulse method, theoretical surface displacements were calculated on the basis of Lamb's theory (Reference [7]). For the reciprocity calibration, reciprocity parameters for the Rayleigh wave calibration were also derived from Lamb's theory. As for the Rayleigh surface wave calibration, a round robin experiment was carried out in a collaborative effort between the USA and Japan, and it was ascertained that absolute sensitivities as obtained by either method agreed well.

The aim of both methods is the same, namely, to establish uniformity of acoustic emission testing, to form a basis for data correlation, and to provide for the interpretation of results obtained by different laboratories at different times.

This Technical Report describes methods for three-transducer calibration, two-transducer calibration, and impulse response calibration, respectively. In three-transducer calibration, three acoustic emission transducers of the same kind, which are reversible transducers, are prepared to configure three independent pairs of transmitting and receiving transducers on a solid transfer medium. Transmission signal current and reception signal voltage are measured on each pair as a function of frequency, and frequency responses of amplitude of absolute sensitivity both to the Rayleigh surface waves and longitudinal waves are determined on each transducer. Once three-transducer calibration has been carried out, an optional transducer, which is not necessarily a reversible transducer, can be calibrated by a relatively simple procedure by using the calibrated transducer as a reference of transmission or reception. In two-transducer calibration, frequency responses of amplitude of absolute reception sensitivity are determined on an optional transducer by using one acoustic emission transducer, the transmission responses of which have been calibrated by the three-transducer calibration. In addition, by means of three-transducer calibration, impulse responses of each acoustic emission transducer can also be determined. In the impulse response calibration, frequency responses of phase angle, in addition to amplitude, of absolute sensitivity are measured by three-transducer calibration on the basis of complex reciprocity parameters, and impulse responses are determined through inverse Fourier transform of the frequency responses of amplitude and phase.

Non-destructive testing — Methods for absolute calibration of acoustic emission transducers by the reciprocity technique

1 Scope

This Technical Report describes the method of three-transducer calibration for calibrating frequency responses of absolute sensitivity by means of a reciprocity technique using three reversible acoustic emission transducers of the same kind, the method of two-transducer calibration for calibrating frequency responses of reception sensitivity of an optional acoustic emission transducer by using one acoustic emission transducer, the transmission responses of which have been calibrated by three-transducer calibration, the method for impulse response calibration for calibrating impulse responses of absolute sensitivity through inverse Fourier transform of the frequency responses measured by the three-transducer calibration, and the method for representing the calibration results.

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 12716:2001, *Non-destructive testing — Acoustic emission inspection — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12716 and the following apply.

3.1
reciprocity technique
calibration method on three reversible acoustic emission transducers of the same kind, wherein transducers are arranged on a solid transfer medium so that they configure three independent pairs of transmitting and receiving transducers, and absolute sensitivity is determined only by electrical measurements of transmission current and reception voltage on each pair

3.2
reversible transducer
transducer which can be used both for transmission and reception

3.3
absolute sensitivity
quantity of reception voltage sensitivity or transmission current response of an acoustic emission transducer

3.4
reception voltage sensitivity
ratio of the open-circuit output voltage of an acoustic emission transducer used for reception to the vertical component of displacement velocity at the position where the transducer is to be placed

3.5
transmission current response
ratio of the vertical component of displacement velocity at the index point to the input current of an acoustic emission transducer used for transmission

3.6
index point
position on the surface of the transfer medium, which is located at the specified distance in the specified direction from the acoustic emission transducer used for transmission, and used as the reference of transmission response

3.7
reciprocity parameter
ratio of reception sensitivity to transmission response of an acoustic emission transducer which is a reversible transducer

3.8
transfer medium
solid block on the surfaces of which transducers are placed in the calibration so that they configure a pair of transmitting and receiving transducers of the Rayleigh surface waves or longitudinal waves

3.9
calibration signal
electrical voltage signal which is applied to the transmitting transducer in the calibration

3.10
tone burst signal
calibration signal consisting of sinusoidal waves with a specified frequency and a specified period modulated so that the envelope forms one squared cosine

3.11
calibration frequency
frequency of sinusoidal waves of which a tone burst signal consists

3.12
squared-cosine signal
calibration signal which trigonometrically increases from zero to a maximum and decreases to zero during a specified period

3.13
Hanning window
cosine-type time window with a specified period, which is used for Fourier transform of transmission and reception signals measured in the impulse response calibration

3.14
Rayleigh wave calibration
calibration by which sensitivity to Rayleigh surface waves is determined by using Rayleigh waves for transmission and reception

3.15
longitudinal wave calibration
calibration by which axial sensitivity to longitudinal waves is determined by using longitudinal waves for transmission and reception

3.16
three-transducer calibration
calibration by a reciprocity technique, wherein frequency responses of amplitude of reception voltage sensitivity and/or transmission current response are determined on each of the three acoustic emission transducers

3.17
two-transducer calibration
calibration on an optional acoustic emission transducer which is not necessarily a reversible transducer, wherein frequency responses of amplitude of reception voltage sensitivity are determined by using one acoustic emission transducer for transmission, the transmission current response of which has been determined by three-transducer calibration

3.18
impulse response calibration
calibration on three reversible acoustic emission transducers of the same kind, wherein impulse responses of reception voltage sensitivity are determined through inverse Fourier transform of the frequency responses of amplitude and phase of absolute sensitivity measured by three-transducer calibration

4 Preparation for calibration

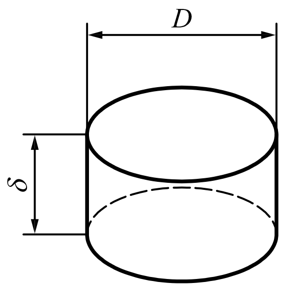
4.1 Transfer medium and calibration signal

The transfer medium should be made of a material whose density and elastic moduli are as close as possible to those of the actual object on which acoustic emission transducers are intended for use. In this Technical Report, carbon steel is principally assumed to be the material of possible objects. While any solid can be used for the transfer medium, forged steel is most recommended. The transfer medium should undergo ultrasonic testing in order to assure that detectable flaws or inclusions, which may affect the Rayleigh wave or longitudinal wave calibration, are not included. Namely, in longitudinal ultrasonic testing at a frequency between 2 MHz and 5 MHz, the medium should contain no flaws which give a reflection greater than 10 % of the first back-wall reflection. The planes of the transfer medium, used for the longitudinal wave calibration, should be parallel within 0,2°.

At the measurement of reception signals in the calibration, discrimination between the direct wave of the Rayleigh waves or longitudinal waves, which is the object of measurement, and other spurious waves is made on the basis of the propagation time of each wave. A larger dimension of the medium causes longer differences in the propagation time between waves, and consequently, the period T of a tone burst signal used in three-transducer or two-transducer calibration, or the period T_w of a Hanning window used in impulse response calibration, can be set longer.

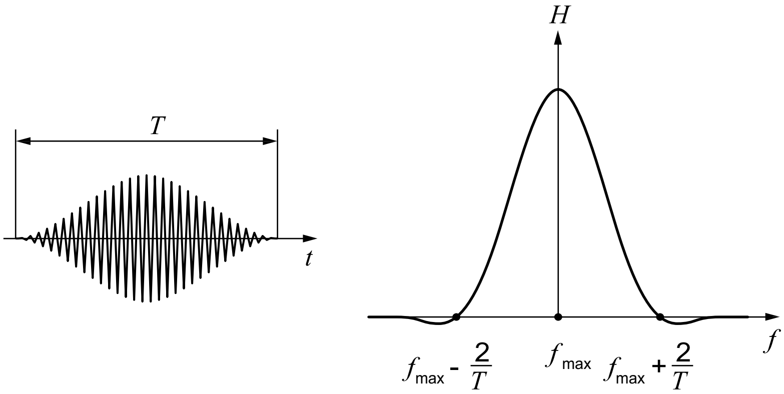
Figure 1 shows examples of setting on the period, T, in seconds, of a tone burst signal or the period, T_w, in seconds, of a Hanning window in relation to the dimension of a cylindrical transfer medium made of forged steel. In general, the shape of the medium is not limited to a cylinder. A rectangular medium, for instance, may be used as long as its volume contains the cylinder.

Figure 2 shows an example of the waveform and frequency spectrum of a tone burst signal with a period, T, in seconds, and a calibration frequency, f_{max}, in hertz.



Diameter D m	**Thickness** δ m	**Tone burst signal period or Hanning window period** T or T_w s
0,4	0,19	0,000 05
0,6	0,38	0,000 1
1,2	0,76	0,000 2

Figure 1 — Dimension of transfer medium and setting of period T or T_w



Key

H amplitude

f frequency

f_{max} maximum calibration frequency

T period

t time

Figure 2 — Waveform and frequency spectrum of a tone burst signal

4.2 Mounting of acoustic emission transducer

Sensitivity of acoustic emission transducers depends on the mounting method, namely, the contact pressure, couplant, and surface roughness of the object. The contact surface pressure of the transducers under calibration should be not less than 0,1 MPa, and machine oil is recommended as the couplant for use on steel. The surfaces of the transfer medium, on which acoustic emission transducers are mounted in calibration, should have a root mean square surface roughness value R, in metres, so that Condition (1) is satisfied:

$$R \le \frac{20}{f_{max}} \quad (1)$$

where f_{max} is the maximum frequency, in hertz, of calibration.

The distance between the transmitting and receiving transducers on the transfer medium should be so set that each transducer is located in a far field of the mating transducer. In Rayleigh wave calibration, the distance, r_R, in metres, should be set so that Condition (2) is satisfied:

$$r_R \ge \frac{f_{max}}{c_R} d^2 \quad (2)$$

In longitudinal wave calibration, the distance, r_L, in metres, should be set so that Condition (3) is satisfied:

$$r_L \ge \frac{f_{max}}{c_L} d^2 \quad (3)$$

where

d is the diameter, in metres, of the transducer element,

c_R, c_L are propagation velocities, in metres per second, of Rayleigh and longitudinal waves in the transfer medium, respectively.

The propagation velocities are given by Equations (4) and (5):

$$c_R = \frac{1}{Y}\left[\frac{E}{2(1+\mu)\rho}\right]^{1/2} \quad (4)$$

$$c_L = \left[\frac{(1-\mu)E}{(1+\mu)(1-2\mu)\rho}\right]^{1/2} \quad (5)$$

where

E is the Young modulus, in newtons per square metre, of the transfer medium;

μ is the Poisson ratio of the transfer medium;

ρ is the density, in kilograms per cubic metre, of the transfer medium;

Y is a constant which depends on the Poisson ratio.

Table 1 shows the numerical values of Y.

4.3 Calculation of reciprocity parameters

Reciprocity parameters, essential both for three-transducer calibration and the impulse-response calibration, are dependent not on the transducer design but on the mode of waves, constants of the medium, and definition of sensitivity. Amplitude $|H_R(f)|$ and phase angle $\angle H_R(f)$ of the reciprocity parameter for Rayleigh wave calibration are given at a frequency, f, in hertz, by Equations (6) and (7), respectively:

$$|H_R(f)| = 2\pi f \frac{1+\mu}{E} k_R X \left(\frac{2}{\pi k_R r_R}\right)^{1/2} \quad (6)$$

$$\angle H_R(f) = \frac{\pi}{4} - k_R r_R \quad (7)$$

where

$$k_R = \frac{2\pi f}{c_R}$$

X is a constant which depends on the Poisson ratio. Table 1 also shows the numerical values of X.

Amplitude $|H_L(f)|$ and phase angle $\angle H_L(f)$ of the reciprocity parameter for longitudinal wave calibration are given at a frequency, f, in hertz, by Equations (8) and (9), respectively:

$$|H_L(f)| = 2f \frac{(1+\mu)(1-2\mu)}{E(1-\mu)r_L} \quad (8)$$

$$\angle H_L(f) = \frac{\pi}{2} - k_L r_L \quad (9)$$

where

$$k_L = \frac{2\pi f}{c_L}$$

Table 1 — Numerical values of constants X and Y

μ	X	Y
0,00	0,284 4	1,144 1
0,25	0,183 5	1,087 7
0,26	0,180 0	1,085 7
0,27	0,176 5	1,083 8
0,28	0,173 1	1,082 0
0,29	0,169 7	1,080 1
0,30	0,166 4	1,078 3
0,31	0,163 1	1,076 5
0,32	0,159 8	1,074 7
0,33	0,156 6	1,073 0
0,34	0,153 5	1,071 2
0,35	0,150 4	1,069 5

5 Method for three-transducer calibration

The method for three-transducer calibration of acoustic emission transducers consists of the measurement of transmission current and reception voltage in Rayleigh wave calibration and/or longitudinal wave calibration, and determination of absolute sensitivity. In three-transducer calibration, a tone burst signal with a period, T, in seconds, and a calibration frequency, f, in hertz, should be used for the calibration signal. The method for each procedure is as stated below.

5.1 Apparatus to be used

a) Three acoustic emission transducers T_1, T_2 and T_3 to be calibrated, which are reversible transducers.

b) Calibration signal generator.

c) Transfer medium.

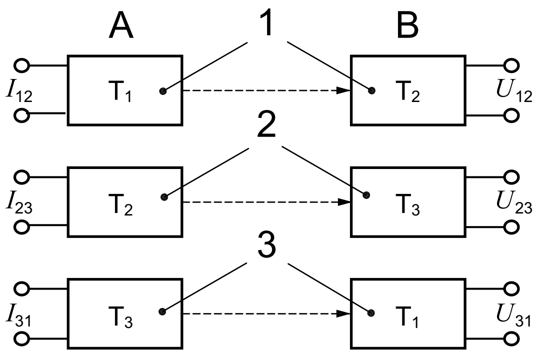
d) Current probe.

e) Waveform display.

5.2 Method of measurement

5.2.1 Measurement in Rayleigh wave calibration

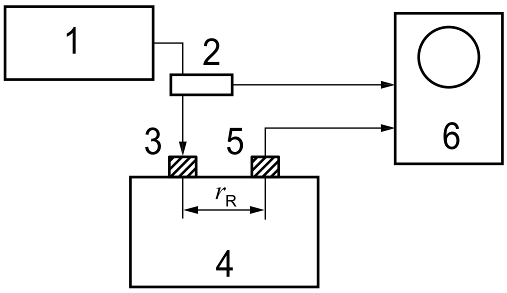
As illustrated in Figure 3, three independent pairs of transmitting and receiving transducers should be configured by means of the three acoustic emission transducers under calibration. Figure 4 shows the instrumentation setup and transducer arrangement for the measurement of Rayleigh wave calibration, where both the transmitting and receiving transducers in each pair are mounted at a distance, r_R , in metres, apart from each other on the same plane of the transfer medium. As illustrated in Figure 5, magnitudes of the transmission current, $|I_R(f)|$, in amperes, and reception voltage, $|U_R(f)|$, in volts, corresponding to the direct Rayleigh wave should be measured on each pair. Measured values of the magnitudes are summarized in Table 2.



Key

A	transmitting transducers	I_{12}, I_{23}, I_{31}	currents
B	receiving transducers	U_{12}, U_{23}, U_{31}	voltages
T_1, T_2, T_3	transducers	1, 2, 3	pairs of transducers

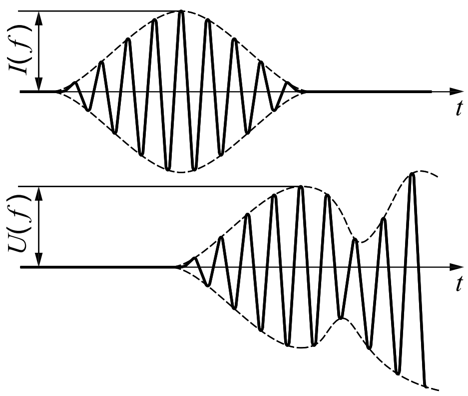
Figure 3 — Three independent pairs of transmitting and receiving transducers



Key

1	calibration signal generator	5	receiving transducer
2	current probe	6	waveform display
3	transmitting transducer		
4	transfer medium	r_R	distance in Rayleigh wave calibration

Figure 4 — Instrumentation setup and transducer arrangement for Rayleigh wave calibration



Key

$I(f)$ transmission current

$U(f)$ reception voltage

t time

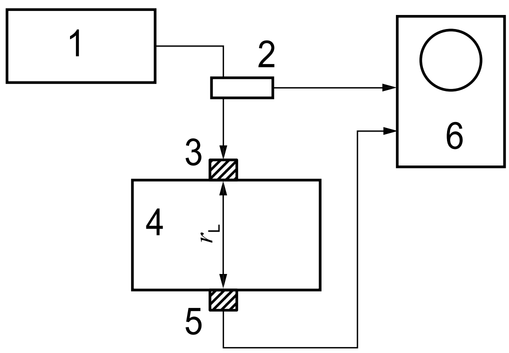
Figure 5 — Measurement of transmission current and reception voltage

Table 2 — Measured values of transmission current and reception voltage in Rayleigh wave calibration

Pair	Transmission transducer	Current	Reception transducer	Voltage
1	T_1	$\lvert I_{R12}(f)\rvert$	T_2	$\lvert U_{R12}(f)\rvert$
2	T_2	$\lvert I_{R23}(f)\rvert$	T_3	$\lvert U_{R23}(f)\rvert$
3	T_3	$\lvert I_{R31}(f)\rvert$	T_1	$\lvert U_{R31}(f)\rvert$

5.2.2 Measurement in longitudinal wave calibration

As illustrated in Figure 3, three independent pairs of transmitting and receiving transducers should be configured by means of the three acoustic emission transducers under calibration. Figure 6 shows the instrumentation setup and transducer arrangement for the measurement of longitudinal wave calibration, where the transmitting and receiving transducers in each pair are mounted with their central axes coinciding on the planes of the transfer medium, parallel to each other with a separation, r_L, in metres. As illustrated in Figure 5, magnitudes of the transmission current, $|I_L(f)|$, in amperes, and reception voltage, $|U_L(f)|$, in volts, corresponding to the direct longitudinal wave should be measured on each pair. Measured values of the magnitudes are summarized in Table 3.



Key

1 calibration signal generator
2 current probe
3 transmitting transducer
4 transfer medium
5 receiving transducer
6 waveform display
r_L distance in longitudinal wave calibration

Figure 6 — Instrumentation setup and transducer arrangement for longitudinal wave calibration

Table 3 — Measured values of transmission current and reception voltage in Rayleigh wave calibration

Pair	Transmission transducer	Current	Reception transducer	Voltage
1	T_1	$\lvert I_{L12}(f)\rvert$	T_2	$\lvert U_{L12}(f)\rvert$
2	T_2	$\lvert I_{L23}(f)\rvert$	T_3	$\lvert U_{L23}(f)\rvert$
3	T_3	$\lvert I_{L31}(f)\rvert$	T_1	$\lvert U_{L31}(f)\rvert$

5.3 Method for determination of absolute sensitivity

5.3.1 Determination of absolute sensitivity in Rayleigh wave calibration

As for the acoustic emission transducer T_1, for instance, reception voltage sensitivity $|M_{R1}(f)|$, in volt seconds per metre, and transmission current response $|S_{R1}(f)|$, metres per second ampere, at a calibration frequency, f, in hertz, should be determined in Rayleigh wave calibration by Equations (10) and (11), respectively, using the measured values summarized in Table 2:

$$\left|M_{R1}(f)\right| = \left(\frac{1}{\left|H_R(f)\right|} \frac{\left|U_{R12}(f)\right|}{\left|I_{R12}(f)\right|} \frac{\left|I_{R23}(f)\right|}{\left|U_{R23}(f)\right|} \frac{\left|U_{R31}(f)\right|}{\left|I_{R31}(f)\right|} \right)^{1/2} \tag{10}$$

$$\left|S_{R1}(f)\right| = \left(\left|H_R(f)\right| \frac{\left|U_{R12}(f)\right|}{\left|I_{R12}(f)\right|} \frac{\left|I_{R23}(f)\right|}{\left|U_{R23}(f)\right|} \frac{\left|U_{R31}(f)\right|}{\left|I_{R31}(f)\right|} \right)^{1/2} \tag{11}$$

where the index point as the reference of the transmission response is located at the position of the receiving transducer in the Rayleigh wave calibration. Similar equations also hold for acoustic emission transducers T_2 and T_3.

5.3.2 Determination of absolute sensitivity in longitudinal wave calibration

As for the acoustic emission transducer T1, for instance, reception voltage sensitivity, $|M_{L1}(f)|$, in volt seconds per metre, and transmission current response, $|S_{L1}(f)|$, in metres per second ampere, at a calibration frequency, f, in hertz, should be determined in longitudinal wave calibration by Equations (12) and (13), respectively, using the measured values summarized in Table 3:

$$\left|M_{L1}(f)\right| = \left(\frac{1}{\left|H_L(f)\right|} \frac{\left|U_{L12}(f)\right|}{\left|I_{L12}(f)\right|} \frac{\left|I_{L23}(f)\right|}{\left|U_{L23}(f)\right|} \frac{\left|U_{L31}(f)\right|}{\left|I_{L31}(f)\right|} \right)^{1/2} \tag{12}$$

$$\left|S_{L1}(f)\right| = \left(\left|H_L(f)\right| \frac{\left|U_{L12}(f)\right|}{\left|I_{L12}(f)\right|} \frac{\left|I_{L23}(f)\right|}{\left|U_{L23}(f)\right|} \frac{\left|U_{L31}(f)\right|}{\left|I_{L31}(f)\right|} \right)^{1/2} \tag{13}$$

where the index point as the reference of the transmission response is located at the position of the receiving transducer in the longitudinal wave calibration. Similar equations also hold for acoustic emission transducers T_2 and T_3.

6 Method for two-transducer calibration

The method for two-transducer calibration of acoustic emission transducers consists of the measurement of transmission current and reception voltage in Rayleigh wave calibration and/or longitudinal wave calibration, and determination of absolute sensitivities. In two-transducer calibration, a tone burst signal with a period, T, in seconds, and a calibration frequency, f_{max}, in hertz should be used for the calibration signal. The method for each procedure is as stated below.

6.1 Apparatus to be used

a) Optional acoustic emission transducer to be calibrated, which is either a reversible or nonreversible transducer.

b) One acoustic emission transducer, the transmission current response of which has been determined by three-transducer calibration.

c) Calibration signal generator.

d) Transfer medium.

e) Current probe.

f) Waveform display.

6.2 Method of measurement

6.2.1 Measurement in Rayleigh wave calibration

Figure 4 shows the instrumentation setup and transducer arrangement for the measurement of Rayleigh wave calibration, where one acoustic emission transducer, the Rayleigh-wave transmission current response of which has been determined by three-transducer calibration, is used for transmission and an optional acoustic emission transducer under calibration is used for reception. The transmitting and receiving transducers are mounted at a distance, r_{R}, in metres, apart from each other on the same plane of the transfer medium. As illustrated in Figure 5, magnitudes of the transmission current $I'_{\mathrm{R}}(f)|$, in amperes, and reception voltage $U'_{\mathrm{R}}(f)|$, in volts, corresponding to the direct Rayleigh wave should be measured on each pair.

6.2.2 Measurement in longitudinal wave calibration

Figure 6 shows the instrumentation setup and transducer arrangement for the measurement of longitudinal wave calibration, where one acoustic emission transducer, the longitudinal-wave transmission current response of which has been determined by three-transducer calibration, is used for transmission and an optional acoustic emission transducer under calibration is used for reception. The transmitting and receiving transducers are mounted with their central axes coinciding on the planes of the transfer medium, parallel to each other with a separation, r_{L}, in metres. As illustrated in Figure 5, magnitudes of the transmission current $I'_{\mathrm{R}}(f)|$, in amperes, and reception voltage $U'_{\mathrm{R}}(f)|$, in volts, corresponding to the direct longitudinal wave should be measured on each pair.

6.3 Method for determination of absolute sensitivity

6.3.1 Determination of absolute sensitivity in Rayleigh wave calibration

Reception voltage sensitivity $M'_{\mathrm{R}}(f)|$, in volt seconds per metre, at a calibration frequency, f, in hertz, of the optional acoustic emission transducer should be determined in Rayleigh wave calibration by Equation (14):

$$\left|M'_{\mathrm{R}}(f)\right| = \frac{1}{\left|S_{\mathrm{R}}(f)\right|} \frac{\left|U'_{\mathrm{R}}(f)\right|}{\left|I'_{\mathrm{R}}(f)\right|} \tag{14}$$

where $|S_{\mathrm{R}}(f)|$, in metres per second ampere, is the Rayleigh-wave transmission current response of the acoustic emission transducer, which has been calibrated by three-transducer calibration.

6.3.2 Determination of absolute sensitivity in longitudinal wave calibration

Reception voltage sensitivity $\left|M'_{\mathrm{L}}(f)\right|$, in volt seconds per metre, at a calibration frequency, f, in hertz, of the optional acoustic emission transducer should be determined in longitudinal wave calibration by Equation (15):

$$\left|M'_{\mathrm{L}}(f)\right| = \frac{1}{\left|S_{\mathrm{L}}(f)\right|} \frac{\left|U'_{\mathrm{L}}(f)\right|}{\left|I'_{\mathrm{L}}(f)\right|} \tag{15}$$

where $|S_{\mathrm{L}}(f)|$, in metres per second ampere, is the longitudinal wave transmission current response of the acoustic emission transducer, which has been calibrated by three-transducer calibration.

7 Method for impulse response calibration

The method for impulse response calibration of acoustic emission transducers consists of the setting of a calibration signal, recording of transmission current and reception voltage waveforms in Rayleigh wave calibration and/or longitudinal wave calibration, determination of frequency responses of absolute sensitivity, and determination of impulse responses through inverse Fourier transform. The method for each procedure is as stated in the following.

7.1 Apparatus to be used

a) Three acoustic emission transducers T_1, T_2 and T_3 to be calibrated, which are reversible transducers.

b) Calibration signal generator.

c) Transfer medium.

d) Current probe.

e) Waveform recorder.

f) Digital computer.

7.2 Method of measurement

7.2.1 Setting of calibration signal

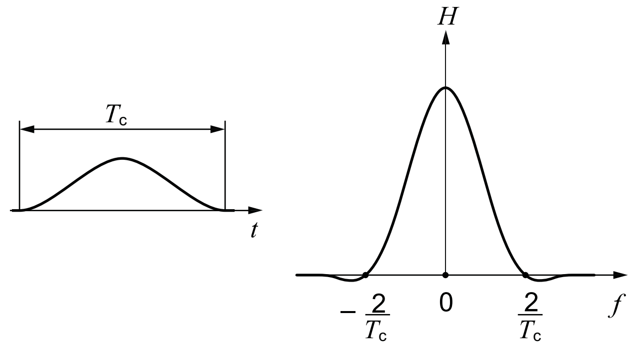
In impulse response calibration, a squared-cosine signal, $u(t)$, in volts, with a period, T_{c}, in seconds, and a magnitude, A, in volts, should be used for the calibration signal. Namely:

$$u(t) = \begin{cases} A\left(\frac{1}{2} + \frac{1}{2}\cos 2\pi \frac{t}{T_{\mathrm{c}}}\right) & \text{if} \quad -\frac{T_{\mathrm{c}}}{2} \le t \le \frac{T_{\mathrm{c}}}{2} \\ 0 & \text{if} \quad t < -\frac{T_{\mathrm{c}}}{2} \ \text{or} \ \frac{T_{\mathrm{c}}}{2} < t \end{cases} \tag{16}$$

The period, T_{c}, in seconds, of a squared-cosine signal should be set so that Equation (17) is satisfied:

$$T_{\mathrm{c}} \approx \frac{1}{f_{\mathrm{max}}} \tag{17}$$

where f_{max}, in hertz, is a maximum frequency of calibration. Figure 7 shows an example of the waveform and frequency spectrum of a squared-cosine signal with a period, T_{c}, in seconds.



Key

H amplitude T_c period

f frequency t time

Figure 7 — Waveform and frequency spectrum of a squared-cosine signal

7.2.2 Recording of waveforms in Rayleigh wave calibration

As illustrated in Figure 3, three independent pairs of transmitting and receiving transducers should be configured by means of the three acoustic emission transducers under calibration. Figure 4 shows the instrumentation setup and transducer arrangement for the measurement of Rayleigh wave calibration, where both the transmitting and receiving transducers in each pair are mounted at a distance, r_R, in metres, apart from each other on the same plane of the transfer medium. Here, a waveform recorder is used in place of a waveform display. As shown in Table 4, waveforms of the transmission current $i_R(t)$, in amperes, and reception voltage, $u_R(t)$, in volts, corresponding to the direct Rayleigh wave are recorded on each pair.

Table 4 — Recorded waveforms of transmission current and reception voltage in Rayleigh wave calibration

Pair	Transmission transducer	Current	Reception transducer	Voltage
1	T_1	$i_{R12}(t)$	T_2	$u_{R12}(t)$
2	T_2	$i_{R23}(t)$	T_3	$u_{R23}(t)$
3	T_3	$i_{R31}(t)$	T_1	$u_{R31}(t)$

7.2.3 Recording of waveforms in longitudinal wave calibration

As illustrated in Figure 3, three independent pairs of transmitting and receiving transducers should be configured by means of the three acoustic emission transducers under calibration. Figure 6 shows the instrumentation setup and transducer arrangement for the measurement of longitudinal wave calibration, where the transmitting and receiving transducers in each pair are mounted with their central axes coinciding on the planes of the transfer medium, parallel to each other with a separation, r_L, in metres. Here, a waveform recorder is used in place of a waveform display. As is shown in Table 5, waveforms of the transmission current, $i_L(t)$, in amperes, and reception voltage $u_L(t)$, in volts, corresponding to the direct longitudinal wave are recorded on each pair.

Table 5 — Recorded waveforms of transmission current and reception voltage in longitudinal wave calibration

Pair	Transmission transducer	Current	Reception transducer	Voltage
1	T_1	$i_{L12}(t)$	T_2	$u_{L12}(t)$
2	T_2	$i_{L23}(t)$	T_3	$u_{L23}(t)$
3	T_3	$i_{L31}(t)$	T_1	$u_{L31}(t)$

7.3 Method for determination of frequency response

7.3.1 Setting of time window

For Fourier transform of transmission current and reception voltage waveforms recorded in the measurement described in the foregoing, a Hanning window $W(t)$ with a period T_W, in seconds, should be used as the time window to clip a portion from each waveform. Namely,

$$W(t) = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos 2\pi \frac{t}{T_W} & \text{if} \quad -\frac{T_W}{2} \le t \le \frac{T_W}{2} \\ 0 & \text{if} \quad t < -\frac{T_W}{2} \quad \text{or} \quad \frac{T_W}{2} < t \end{cases} \tag{18}$$

7.3.2 Determination of frequency response in Rayleigh wave calibration

As is shown in Table 6, Fourier transform of the transmission current and reception voltage waveforms recorded in the Rayleigh wave calibration should be carried out by using the Hanning window. Consequently, amplitude and phase of the frequency spectrum of the transmission current $i_{R12}(t)$, in amperes, for instance, are given by Equations (19) and (20), respectively:

$$\left| I_{R12}(f) \right| = \left| \int_{-T_W/2}^{T_W/2} i_{R12}(t)\, W(t) \exp(\mathrm{j}2\pi ft).\, \mathrm{d}t \right| \tag{19}$$

$$\angle I_{R12}(f) = \angle \left[\int_{-T_W/2}^{T_W/2} i_{R12}(t)\, W(t) \exp(\mathrm{j}2\pi ft)\, .\mathrm{d}t \right] \tag{20}$$

Amplitude and phase of the frequency spectrum of the reception voltage, $u_{R12}(t)$, in volts, for instance, are given by Equations (21) and (22), respectively:

$$\left| U_{R12}(f) \right| = \left| \int_{\Delta t_R - (T_W/2)}^{\Delta t_R + (T_W/2)} u_{R12}(t)\, W(t - \Delta t_R) \exp(\mathrm{j}2\pi ft).\, \mathrm{d}t \right| \tag{21}$$

$$\angle U_{R12}(f) = \angle \left[\int_{\Delta t_R - (T_W/2)}^{\Delta t_R + (T_W/2)} u_{R12}(t)\, W(t - \Delta t_R) \exp(\mathrm{j}2\pi ft)\, .\mathrm{d}t \right] \tag{22}$$

where Δt_R, in seconds, is the propagation time of the Rayleigh wave from the transmitting transducer to the receiving transducer, which is given by Equation (23):

$$\Delta t_R = \frac{r_R}{c_R} \tag{23}$$

Table 6 — Frequency spectra of transmission current and reception voltage in Rayleigh wave calibration

Pair	Transmission current		Reception voltage	
	Amplitude	Phase angle	Amplitude	Phase angle
1	$\lvert I_{R12}(f)\rvert$	$\angle I_{R12}(f)$	$\lvert U_{R12}(f)\rvert$	$\angle U_{R12}(f)$
2	$\lvert I_{R23}(f)\rvert$	$\angle I_{R23}(f)$	$\lvert U_{R23}(f)\rvert$	$\angle U_{R23}(f)$
3	$\lvert I_{R31}(f)\rvert$	$\angle I_{R31}(f)$	$\lvert U_{R31}(f)\rvert$	$\angle U_{R31}(f)$

As for the acoustic emission transducer T_1, for instance, frequency responses of amplitude $|M_{R1}(f)|$, in volt seconds per metre, and phase angle, $\Psi_{R1}(f)$, in radians, of reception voltage sensitivity, should be determined in Rayleigh wave calibration by Equations (24) and (25), respectively, using the frequency spectra summarized in Table 6:

$$\left|M_{R1}(f)\right| = \left(\frac{1}{\left|H_R(f)\right|}\frac{\left|U_{R12}(f)\right|}{\left|I_{R12}(f)\right|}\frac{\left|I_{R23}(f)\right|}{\left|U_{R23}(f)\right|}\frac{\left|U_{R31}(f)\right|}{\left|I_{R31}(f)\right|}\right)^{1/2} \quad (24)$$

$$\Psi_{R1}(f) = \frac{1}{2}\Big\{-\angle H_R(f) + \left[\angle U_{R12}(f) - \angle I_{R12}(f)\right] + \left[\angle I_{R23}(f) - \angle U_{R23}(f)\right] + \left[\angle U_{R31}(f) - \angle I_{R31}(f)\right]\Big\} \quad (25)$$

Similar equations also hold for the acoustic emission transducers T_2 and T_3.

7.3.3 Determination of frequency response in longitudinal wave calibration

As is shown in Table 7, Fourier transform of the transmission current and reception voltage waveforms recorded in the longitudinal wave calibration should be carried out by using the Hanning window. Consequently, amplitude and phase of the frequency spectrum of the transmission current $i_{L12}(t)$, in amperes, for instance, are given by Equations (26) and (27), respectively:

$$\left|I_{L12}(f)\right| = \left|\int_{-T_w/2}^{T_w/2} i_{L12}(t)\,W(t)\exp(j2\pi ft)\,.dt\right| \quad (26)$$

$$\angle I_{L12}(f) = \angle\left[\int_{-T_w/2}^{T_w/2} i_{L12}(t)\,W(t)\exp(j2\pi ft).\,dt\right] \quad (27)$$

Amplitude and phase of the frequency spectrum of the reception voltage $u_{L12}(t)$, in volts, for instance, are given by Equations (28) and (29), respectively:

$$\left|U_{L12}(f)\right| = \left|\int_{\Delta t_L-(T_w/2)}^{\Delta t_L+(T_w/2)} u_{L12}(t)\,W(t-\Delta t_L)\exp(j2\pi ft)\,.dt\right| \quad (28)$$

$$\angle U_{L12}(f) = \angle\left[\int_{\Delta t_L-(T_w/2)}^{\Delta t_L+(T_w/2)} u_{L12}(t)\,W(t-\Delta t_L)\exp(j2\pi ft)\,.dt\right] \quad (29)$$

where Δt_L, in seconds, is the propagation time of the longitudinal wave from the transmitting transducer to the receiving transducer, which is given by Equation (30):

$$\Delta t_L = \frac{r_L}{c_L} \tag{30}$$

Table 7 — Frequency spectra of transmission current and reception voltage in longitudinal wave calibration

Pair	Transmission current		Reception voltage	
	Amplitude	Phase angle	Amplitude	Phase angle
1	$\lvert I_{L12}(f)\rvert$	$\angle I_{L12}(f)$	$\lvert U_{L12}(f)\rvert$	$\angle U_{L12}(f)$
2	$\lvert I_{L23}(f)\rvert$	$\angle I_{L23}(f)$	$\lvert U_{L23}(f)\rvert$	$\angle U_{L23}(f)$
3	$\lvert I_{L31}(f)\rvert$	$\angle I_{L31}(f)$	$\lvert U_{L31}(f)\rvert$	$\angle U_{L31}(f)$

As for the acoustic emission transducer T_1, for instance, frequency responses of amplitude $|M_{L1}(f)|$, in volt seconds per metre, and phase angle, $\Psi_{L1}(f)$, in radians, of reception voltage sensitivity, should be determined in longitudinal wave calibration by Equations (31) and (32), respectively, using the frequency spectra summarized in Table 7:

$$\left|M_{L1}(f)\right| = \left(\frac{1}{\left|H_L(f)\right|} \frac{\left|U_{L12}(f)\right|}{\left|I_{L12}(f)\right|} \frac{\left|I_{L23}(f)\right|}{\left|U_{L23}(f)\right|} \frac{\left|U_{L31}(f)\right|}{\left|I_{L31}(f)\right|} \right)^{1/2} \tag{31}$$

$$\begin{aligned}\Psi_{L1}(f) = \frac{1}{2}\Big\{ & -\angle H_L(f) + \left[\angle U_{L12}(f) - \angle I_{L12}(f)\right] + \\ & \left[\angle I_{L23}(f) - \angle U_{L23}(f)\right] + \left[\angle U_{L31}(f) - \angle I_{L31}(f)\right]\Big\}\end{aligned} \tag{32}$$

Similar equations also hold for acoustic emission transducers T_2 and T_3.

7.4 Method for determination of impulse response

7.4.1 Determination of impulse response in Rayleigh wave calibration

Impulse response of acoustic emission transducers should be determined in Rayleigh wave calibration through inverse Fourier transform of frequency responses of amplitude and phase angle of the Rayleigh-wave reception voltage sensitivity. As for the acoustic emission transducer T_1, for instance, impulse response $m_{R1}(t)$, in volt seconds per metre second, of the Rayleigh-wave reception voltage sensitivity is given by Equation (33):

$$m_{R1}(t) = \int_{-2f_{max}}^{2f_{max}} \left|M_{R1}(f)\right| \exp\left\{ j\left[2\pi ft + \Psi_{R1}(f)\right]\right\} .df \tag{33}$$

Similar equations also hold for acoustic emission transducers T_2 and T_3.

7.4.2 Determination of impulse response in longitudinal wave calibration

Impulse response of acoustic emission transducers should be determined in longitudinal wave calibration through inverse Fourier transform of frequency responses of amplitude and phase angle of the longitudinal-wave reception voltage sensitivity. As for the acoustic emission transducer T_1, for instance, impulse response

$m_{L1}(t)$, in volt seconds per metre second, of the longitudinal wave reception voltage sensitivity is given by Equation (34):

$$m_{L1}(t) = \int_{-2f_{max}}^{2f_{max}} \left|M_{L1}(f)\right| \exp\left\{j\left[2\pi ft + \Psi_{L1}(f)\right]\right\}.df \quad (34)$$

Similar equations also hold for the acoustic emission transducers T_2 and T_3.

8 Method for representing calibration results

Calibration results should be represented as follows.

8.1 Representation items for calibration results

Calibration results should be represented with the following items.

a) Date of calibration.

b) Name of calibrator.

c) Method of calibration (three-transducer calibration, two-transducer calibration, or impulse response calibration).

d) Apparatus used.

e) Calibration conditions:

   1) Material and dimension of transfer medium;

   2) Distance between transmitting and receiving transducers (r_R or r_L);

   3) Waveform and period (T or T_c) of calibration signal;

   4) Contact surface pressure and couplant.

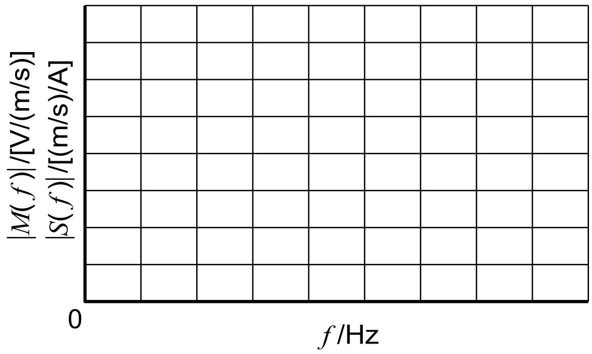
f) Frequency response or impulse response of absolute sensitivity.

8.2 Method for representing frequency response of absolute sensitivity

Three-transducer calibration and/or two-transducer calibration should be carried out repeatedly at different frequencies, f, in hertz, with equal intervals Δf, in hertz, covering the targeted frequency range of calibration so that frequency response of absolute sensitivity is determined. The interval of calibration frequency Δf, in hertz, should be set, in correlation with a period, T, in seconds, of the tone burst signal, to satisfy Condition (35):

$$\Delta f \le \frac{2}{T} \quad (35)$$

The frequency response of absolute sensitivity should be represented by plotting calibration frequency, f, in hertz, on the abscissa in a linear scale, and reception voltage sensitivity, $|M(f)|$, in volt seconds per metre, or transmission current response, $|S(f)|$, in metre amperes per second, on the ordinate in a linear scale as shown in Figure 8. The ordinate may have a logarithmic scale in place of a linear scale.



Key

|M(f)| reception voltage sensitivity

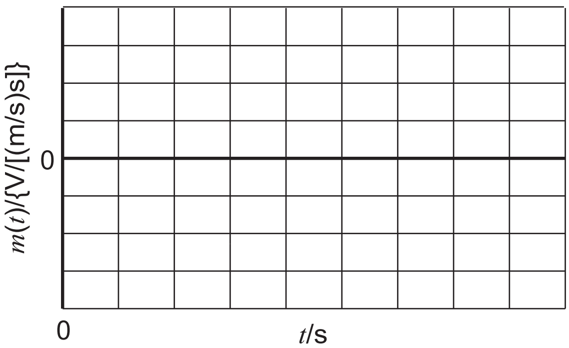
|S(f)| transmission current response

f frequency

Figure 8 — Method for representing frequency response of absolute sensitivity for Rayleigh wave calibration or longitudinal wave calibration

8.3 Method for representing impulse response of absolute sensitivity

Impulse response of absolute sensitivity determined by impulse response calibration should be represented by plotting time, t, in seconds, on the abscissa in a linear scale and impulse response $m(t)$, in volt seconds per metre second, on the ordinate in a linear scale as shown in Figure 9.



Key

$m(t)$ impulse response

t time

Figure 9 — Method for representing impulse response of absolute sensitivity for Rayleigh wave calibration or longitudinal wave calibration

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