INTERNATIONAL STANDARD

ISO 12714

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Non-destructive testing — Acoustic emission inspection — Secondary calibration of acoustic emission sensors

Essais non destructifs — Contrôle par émission acoustique — Étalonnage secondaire des capteurs d'émission acoustique

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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 3.

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.

International Standard ISO 12714 was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 3, *Acoustical methods*.

Introduction

The acoustic emission method of non-destructive testing is addressed by SC3 on acoustical methods of TC 135 on non-destructive testing. Standards for general procedures and requirements are required in order to insure quantitative results and wide applicability. This International Standard addresses the transfer of calibration, or secondary calibration, of acoustic emission sensors. In this method, the device under test is calibrated by comparison with a sensor that has previously undergone primary calibration. The sensor used for comparison is called the reference or secondary standard sensor. The aim of this International Standard is to establish uniformity of acoustic emission testing by standardizing the methods used to transfer calibrations of sensors.

Non-destructive testing — Acoustic emission inspection — Secondary calibration of acoustic emission sensors

1 Scope

This International Standard specifies a method for the secondary calibration of acoustic emission sensors as receivers of elastic waves at the surface of a solid medium. The International Standard is applicable to laboratory tertiary standard sensors and acoustic emission applications sensors.

The secondary calibration yields the frequency response of a sensor to waves of a type normally encountered in acoustic emission work, namely Rayleigh waves. The source producing the signal used for the calibration is mounted on the same surface of a test block as the sensor under test (SUT). The sensitivity of the sensor is determined for excitation within the range of 100 kHz to 1 MHz. Sensitivity values are usually determined at frequencies approximately 10 kHz apart. The units of the calibration are volts per unit of mechanical input (displacement, velocity or acceleration).

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 12713:1998, *Non-destructive testing — Acoustic emission inspection — Primary calibration of transducers.*

ISO 12716:—[1)], *Non-destructive testing — Acoustic emission inspection — Vocabulary.*

ASTM E114-95, *Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Testing by the Contact Method.*

ASTM E1106-86(1992)e1, *Standard Method for Primary Calibration of Acoustic Emission Sensors.*

ASTM E1316-97b, *Standard terminology for Nondestructive Examinations.*

3 Terms and definitions

For the purposes of this International Standard the terms and definitions in ISO 12716 and in ASTM E 1316 as well as the following apply.

3.1 reference sensor (RS)
sensor which has had its response established by primary calibration – see ASTM E 1106 or ISO 12713

NOTE Also called secondary standard sensor.

[1)] To be published.

3.2 secondary calibration
procedure for measuring the frequency or transient response of an acoustic emission sensor by comparison with an RS

3.3 test block
block of homogeneous, isotropic elastic material on which a source, an RS and a SUT are placed for carrying out secondary calibration

4 Abbreviations

AE: acoustic emission

ASTM: American Society for Testing and Materials

FFT: fast Fourier transform

ISO: International Organization for Standardization

RS: reference sensor

SUT: sensor under test

5 General requirements

5.1 Sensor Under Test

This method is applicable to the absolute calibration of normal motion sensors for use as tertiary standards and to the calibration of acoustic emission sensors for use in AE sensing. For tertiary standards purposes, the sensor being calibrated should be of a small aperture, high-fidelity type (such as the NBS Conical Transducer). In general, results from any sensor will be degraded by large aperture and lack of flatness of frequency response.

The stated accuracy applies only if the sensor being calibrated is highly damped. The signal from the sensor following the shock excitation of the calibration signal should be damped to an insignificant level (20 % of peak signal) within the time (30 μs for the prototype secondary calibration system) of the allowed capture window, limited by echoes from boundaries of the calibration block. If this condition is violated, calibration accuracy will suffer. (See 8.1.)

5.2 Units for the Calibration

Secondary calibration produces the same type of information about a sensor as does primary calibration. An AE sensor responds to motion at its front face. The actual stress and strain at the front face of a mounted sensor depends on the interaction between the mechanical impedance of the sensor (load) and that of the mounting block (driver); neither the stress nor the strain is amenable to direct measurement at this location. However, the free displacement that would occur at the surface of the block in the absence of the sensor can be inferred from measurements made elsewhere on the surface. Since AE sensors are used to monitor motion at a free surface of a structure and interactive effects between sensor and structure are generally of no interest, the free motion is the appropriate input variable. It is required therefore, that the units of calibration be volts per unit of free displacement or free velocity, i.e. volts per meter or volt seconds per meter.

The calibration results may be expressed in the frequency domain as the steady-state magnitude and phase response of the sensor to steady-state sinusoidal excitation, or in the time domain as the transient response of the sensor to a delta function of displacement.

5.3 Importance of the test block material

The specific acoustical impedance (Z_{ac}) of the test block is an important parameter which affects the calibration results. Calibrations performed on blocks of different materials yield sensor sensitivities that are very different, e.g., a sensor that has been calibrated on a steel block, if calibrated on a glass or aluminum block, may have an average sensitivity that is 50 % of the value obtained on steel, and, if calibrated on a polymethyl methacrylate block, may have an average sensitivity that is 3 % of the value obtained on steel [2].

For a sensor having a circular aperture (mounting face) with uniform sensitivity over the face, there are frequencies at which nulls in the frequency response occur. These nulls occur at the zeroes of the first order Bessel function, $J_1(ka)$, where $k = 2\pi f/c$, f is frequency, c is the Rayleigh speed in the test block and a is the radius of the sensor face [2]. Therefore, calibration results depend upon the Rayleigh wave speed in the material of the test block.

For the reasons outlined in the previous two paragraphs, all secondary calibration results are specific to a particular material; a secondary calibration procedure must specify the material of the block. Although this International Standard addresses secondary calibrations on test blocks of different materials, the only existing primary calibrations are performed on steel test blocks. To establish a secondary calibration on another material would also require the establishing of a primary calibration for the same material.

6 Requirements of the secondary calibration apparatus

6.1 Basic Scheme

A prototype apparatus for secondary calibration is shown in Figure 1. A glass-capillary-break device or other suitable source device (A) is deployed on the upper face of the steel test block (B). The RS (C) and the SUT (D) are placed equally distant from the source and in opposite directions from it. Because of the symmetry of the sensor placement, the free surface displacements at the locations of the RS and the SUT are the same. Voltage transients from the two sensors are recorded simultaneously by digital waveform recorders (E) and processed by a computer.

Actual dynamic displacements of the surface of the test block at the locations of the RS and the SUT may be different because the RS and the SUT may present different load impedances to the test block. However, consistent with definitions used for primary and secondary calibration, the loading effects of both sensors are considered to be characteristics of the sensors themselves, and calibration results are stated in terms of free displacement of the block surface.

6.2 Qualification of the test block

The prototype secondary calibration apparatus was designed for sensors intended for use on steel. The test block is therefore, made of steel (hot rolled steel A36 material). For a steel block, it is recommended that specification to the metal supplier require that the block be stress relieved at 566 °C or greater and that the stress relief be carried out subsequent to any flame cutting.

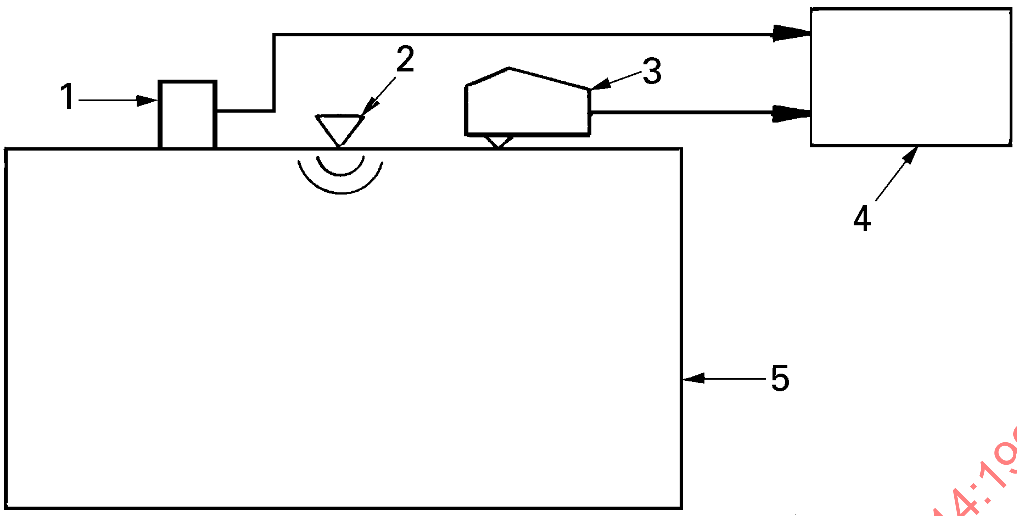
For a steel test block, there shall be two parallel faces with a thickness, measured between the faces, of at least 180 mm. The volume of the block shall contain a cylinder which is 400 mm in diameter by 180 mm long, and the two faces shall be flat and parallel to within 0,12 mm overall (± 0,06 mm).

For a steel test block, the top surface of the block (the working face) shall have an RMS roughness value no greater than 1 µm, as determined by at least three profilometer traces taken in the central region of the block. The bottom surface of the block must have an RMS roughness value no greater than 4 µm. The reason for having a specification on the bottom surface is to assure reasonable ability to perform time-of-flight measurements of the speed of sound in the block.

For blocks of materials other than steel, minimum dimensional requirements, dimensional accuracies and the roughness limitation shall be scaled in proportion to the longitudinal sound speed in the block material relative to that in steel.

The top face of the block shall be the working face on which are located the source, RS and SUT. These locations shall be chosen near the centre so as to maximize the distances of source and receivers to the nearest edge of the face. For a test block of any material, the distance from the source to the RS and the distance from the source to the SUT shall each be 100 mm ± 2 mm (the same as that specified for primary calibration).

The block shall undergo longitudinal ultrasonic inspection for flaws at a frequency between 2 MHz and 5 MHz. Procedure in accordance with ASTM E 114 shall be followed. The block shall contain no flaws which give a reflection greater than 12 % of the first back wall reflection.



Key

1 Sensor under test

2 Capillary-break source

3 Reference sensor

4 Two-channel waveform recorder system

5 41 cm × 41 cm × 19 cm steel block

Figure 1 — Schematic representation of the prototype secondary calibration apparatus

The material of the block shall be highly uniform as determined by pulse-echo and time-of-flight measurements of both longitudinal and shear speeds. These measurements shall be made through the block at a minimum of seven locations regularly spaced over the surface. The uncertainty of each measurement of time of flight shall be no greater than 0,1 %. It is recommended that the pulse-echo transducer have its main resonance in the range between 2 MHz and 5 MHz. For the seven (or more) measurements of longitudinal wave velocity, the maximum difference between the individual values of the measurements shall be no more than 0,3 % of the average value. The measurements of shear wave velocity shall satisfy the same criterion.

6.3 The source

The source employed in the prototype secondary calibration system is a breaking glass capillary. The capillaries are prepared by drawing down 6 mm Pyrex tubing to a diameter of 0,1 mm to 0,25 mm. Source events are generated by squeezing the capillary tubing against the test block using pressure from the side of a 4 mm diameter glass rod held in the hand.

In general, a secondary calibration source may be any small aperture device which can provide sufficient energy to conveniently make the calibration measurements at all frequencies within the range from 100 kHz to 1 MHz. Depending on the calibration technique the source could be a transient device such as the glass-break apparatus, a spark apparatus, a pulse-driven transducer or a continuous wave device such as an NBS conical transducer driven by a tone burst generator. If the RS and SUT are to be tested on the block sequentially instead of simultaneously, then it shall be established that the source is repeatable within 2 %.

6.4 The reference sensor

The RS in the prototype secondary calibration system is an NBS conical transducer. In general, the RS shall have a frequency response, as determined by primary calibration, which is flat over the frequency range of 100 kHz to 1 MHz within a total overall variation of 20 dB either as a velocity sensor or as a displacement sensor. It is preferred that the RS be of a type that has a small aperture, and that its frequency response be as smooth as possible. See 5.3 and Figure 8 concerning the aperture effect.

6.5 The sensor under test

The SUT shall be tested under conditions that are the same as those intended for the SUT when in use. The couplant, the electrical load applied to the SUT terminals, and the hold down force shall all be the same as those that will be applied to the SUT when in use. The preferred couplant is low viscosity machine oil, the electrical load may be anything reasonable and the preferred hold-down force is 9,8 N. These conditions are all the same as for primary calibration.

6.6 Data recording and processing equipment

For methods using transient sources, the instrumentation would comprise a computer and two synchronized transient recorders, one for the RS channel and one for the SUT channel. The transient recorders shall be capable of at least 8 bit accuracy and a sampling rate of 20 MHz, or at least 10 bit accuracy and a sampling rate of 10 MHz. They must each be capable of storing data for a time record of at least 55 µs. The data are transferred to the computer for processing and also stored in a permanent device, e.g., floppy disc, as a permanent record.

7 Calibration data processing

7.1 Raw data

In the prototype secondary calibration system, the raw captured waveform record of one of the two channels comprises 2 048 ten-bit data with a sampling interval Δt = 0,05 µs. Therefore the total record has a length of T = 102,4 µs. Reflections from the bottom of the block appear approximately 60 µs after the beginning of the record in both channels (See Figures 3 and 4). It is undesirable to have the reflections present in the captured waveforms because the reflected rays arrive at the sensors from directions that are different from those that are intended for the calibration. The records are each truncated and padded as follows: data corresponding to times greater than 55 µs are replaced by values, all equal to the average of the last ten values in the record prior to the 55 µs cutoff.

7.2 Complex valued spectra

Using a Fast Fourier Transform (FFT), complex valued spectra $S(f_m)$ and $U(f_m)$ derived from the RS and from the SUT, respectively, are calculated:

$$S(f_m) = \sum_{j=0}^{n-1} s_j \exp(i2\pi mj / n)$$

$$U(f_m) = \sum_{j=0}^{n-1} u_j \exp(i2\pi mj / n)$$

where

n = 2 048,

j = 0,1,2,..., $n - 1$,

s_j = the jth sample value in the RS channel,

u_j = the jth sample value in the SUT channel,

m = 0, 1, 2, ..., $n/2 - 1$,

$f_m = m/T$ is the mth frequency in MHz.

Frequency separation is $1/T$ = 9,76 kHz. It is assumed that s_j and u_j have been converted to volts by taking account of the gains of the waveform recorders and any preamplifiers used in the calibration. The (complex valued) response of the SUT is:

$$D(f_m) = \frac{U(f_m)S_0(f_m)}{S(f_m)}$$

where $S_0(f_m)$ represents the (complex valued) response of the RS in volts per meter at the frequency f_m. The values of $S_0(f_m)$ are derived from primary calibration of the RS.

7.3 Magnitude and phase

The magnitude, r_m, and phase, ω_m, of $D(f_m)$ are calculated from $D(f_m)$ in the usual way:

$$r_m = |D(f_m)|$$

$$\omega_m = \arctan \frac{Iz[D(f_m)]}{Rz[D(f_m)]}$$

where Iz and Rz respectively denote the imaginary and real parts of a complex argument, z. Calibration magnitude data, w_m, are usually expressed in decibels as follows:

$$w_m = 20 \log_{10}(r_m)$$

The values of w_m and ω_m are plotted versus frequency as shown in Figures 5 and 6.

7.4 Special considerations

The FFT treats the function as though it were periodic with period equal to the length of the time recorded. If initial and final values are unequal then a step exists between the last and the first data point. The FFT produces data that are contaminated by the spectrum of this step.

The fix that is applied in the prototype system is to add a linear function to the data as follows:

$$s'_j = s_j + (j/n)(s_0 - s_{n-1})$$

$$u'_j = u_j + (j/n)(u_0 - u_{n-1})$$

The modified functions, s'_j and u'_j, have no steps between the last and first data points. It has been shown analytically [7] that this procedure and two other commonly used techniques for dealing with step-like functions are all equivalent except at zero frequency. This linear "ramp" function is applied to the data after the padding operation.

The phase associated with a complex valued quantity is not uniquely determined. In the prototype system, first a four-quadrant arctangent routine chooses that value of ω_m which lies in the interval between $-\pi$ and $+\pi$. Using this routine, jumps in ω_m occur whenever the value of ω_m crosses one of its limits, $-\pi$ or $+\pi$. To avoid these jumps, a calculation routine in a sequence of increasing frequency adds a multiple of 2π to ω_m so that each value of ω_m is the nearest to the preceding one. For most sensors, this routine produces smooth phase versus frequency curves except when $D(f_m)$ approaches zero. In this event, phase sometimes jumps by a multiple of 2π. For a sensor with relatively flat frequency response, the routine works well, but if the phase response oscillates wildly, or if the magnitude response approaches zero, there exists a phase ambiguity which is a multiple of 2π.

8 Expected uncertainty

8.1 Sources of uncertainty

There are several sources of uncertainty that affect the accuracy and repeatability of the prototype secondary calibration method. Uncertainties involved in the (primary) calibration of the RS and variability in the mounting of the SUT as well as uncertainties introduced in the waveform recording and digital processing all contribute to uncertainty of the secondary calibration result.

The repeatability between calibrations of a sensor with remounting is poorer than without remounting. Making a repeatable mechanical coupling of a sensor to a surface is known to be a problem. In a secondary calibration procedure, special care shall be taken to minimize variability due to the following:

- lack of flatness of the mounting face of the sensor;
- the presence of small burrs on the surface of the test block;
- dirt in the couplant layer; excessive viscosity of the couplant;
- variability in the amount or point of application of the hold-down force.

There is a truncation error arising from the fact that the captured waveform is limited to 55 µs. The SUT is shock-excited primarily by the Rayleigh pulse; the waveform termination is approximately 30 µs later. Electrical output from the sensor is lost if it occurs after this interval. For a sensor which has a ring-down time of less than 30 µs, negligible error will occur, but to the extent to which there is ringing in progress at the end of the interval, the captured waveform will be an erroneous representation of the true response of the sensor. Assessment of truncation error is difficult. A larger test block would allow longer waveform captures, but is not considered practical. The only reasonable solution is to restrict calibration to sensors that are highly damped.

The Fourier transform yields discrete frequency components separated by approximately 10 kHz. At frequencies below 100 kHz, this scale becomes rather coarse. For sensors that have smooth frequency responses, there is meaningful information in the 10 kHz to 100 kHz range, but it is difficult to establish an expected uncertainty in this range.

Electronic noise and quantization noise become progressively worse at high frequencies. At frequencies above 1 MHz, these effects result in a variability of several dB in successive calibrations of the same sensor. Therefore, the frequency band within which it is reasonable to establish error limits is from 100 kHz to 1 MHz.

8.2 Quantitative assessment of uncertainty

Uncertainties of the frequency response magnitude data may be classified as:

- Type A: those which are evaluated by statistical analysis of frequency response magnitude data for many different transducers.
- Type B: those which are derived from the specifications and independently-known performance characteristics of the equipment used for data collection and processing.

For the prototype secondary calibration system, Type A uncertainties are attributed to such things as variations in sensor coupling, variations of amplifier gain, and temperature and aging effects on the sensor. Collectively, these effects impose a multiplicative uncertainty which affects all values of frequency response magnitude data by the same fractional amount, which is estimated to be 16 %, calculated at the 95 % level of statistical confidence.

Type B uncertainties are associated with electrical noise, digital round-off, aliasing errors, and any other errors associated with the transient capture process. The magnitudes of these effects are established by the choice of equipment settings. Collectively, these effects impose the same additive uncertainty on all values of frequency response magnitude data. The total additive uncertainty can be expressed as a fraction of the full scale input range of the equipment. Tests of the performance of digital waveform recording equipment readily available from commercial sources indicate that it is feasible to achieve total additive uncertainties at as low as 3 % of the full scale input range, calculated at the 95 % level of statistical confidence. When equipment settings are chosen to optimize dynamic range, expression of the additive uncertainty can be simplified by stating it as a fraction of the largest individual value from the set of data collected by the equipment. The additive uncertainty of the frequency response magnitude data for any test is therefore stated as 3 % of the maximum value of frequency response magnitude data for that test.

The procedure for calculating combined uncertainties for this method must take into account both the additive and multiplicative components. The multiplicative component for any frequency response magnitude r_m is simply 0,16 r_m. The additive component is equal to 0,03 r_{max} , where r_{max} is the largest value of r for a given data set. The total uncertainty $U(r_m)$ is equal to the quadrature sum of the two components:

$$U(r_m) = [(0{,}16\ r_m)^2 + (0{,}03\ r_{max})^2]^{1/2}$$

$$= (0{,}026\ r_m^{\ 2} + 0{,}001\ r_{max}^{\ 2})^{1/2}$$

$$= r_m[0{,}026 + 0{,}001\ (r_{max}/r_m)^2]^{1/2}$$

The minimum value of $U(r_m)$ is 16,3 %, for the largest value of r_m. The upper limit of $U(r_m)$ depends on the choice of the lowest credible value of r_m. If this is r_{min}, the lowest credible value of r_m, is taken to 20 dB lower than r_{max}, the maximum value of $U(r_m)$ is 35,5 %. The maximum value of $U(r_m)$ can be reduced by truncating the results at higher values of r_{min}.

8.3 Expression of uncertainty in decibels

Values of U may be expressed in dB using:

$$U_{dB} = 20\ \log_{10}[1 \pm U(r_m)]$$

Taking the more conservative result of each sum and difference calculation, $U(r_{max})$ = 1,5 dB and $U(r_{min})$ = 3,8 dB.

9 Proof testing of a secondary calibration system

It shall be demonstrated by calibration of at least three sensors that the secondary calibration system produces repeatable resu0lts. For each of the three sensors, 95 % of the calibration frequency response data must fall within an error band defined by $\pm U$.

It shall be demonstrated that for at least one sensor the results of the secondary calibration are in agreement with those of a primary calibration. For this sensor, 95 % of the calibration frequency response data shall agree with primary calibration data within an error band defined by $\pm (U + 1{,}5)$.

10 Typical calibration results

Figures 2 and 3 show typical waveform captures from the RS and the SUT, respectively, as obtained on the prototype secondary calibration system. Figures 4 and 5 show calibration frequency domain results obtained from the data of Figures 2 and 3. Figures 6, 7, and 8 show comparison of results from the primary calibration and from the prototype secondary calibration respectively, carried out on three sensors. Each of the two curves in each figure displays the results of a single calibration.

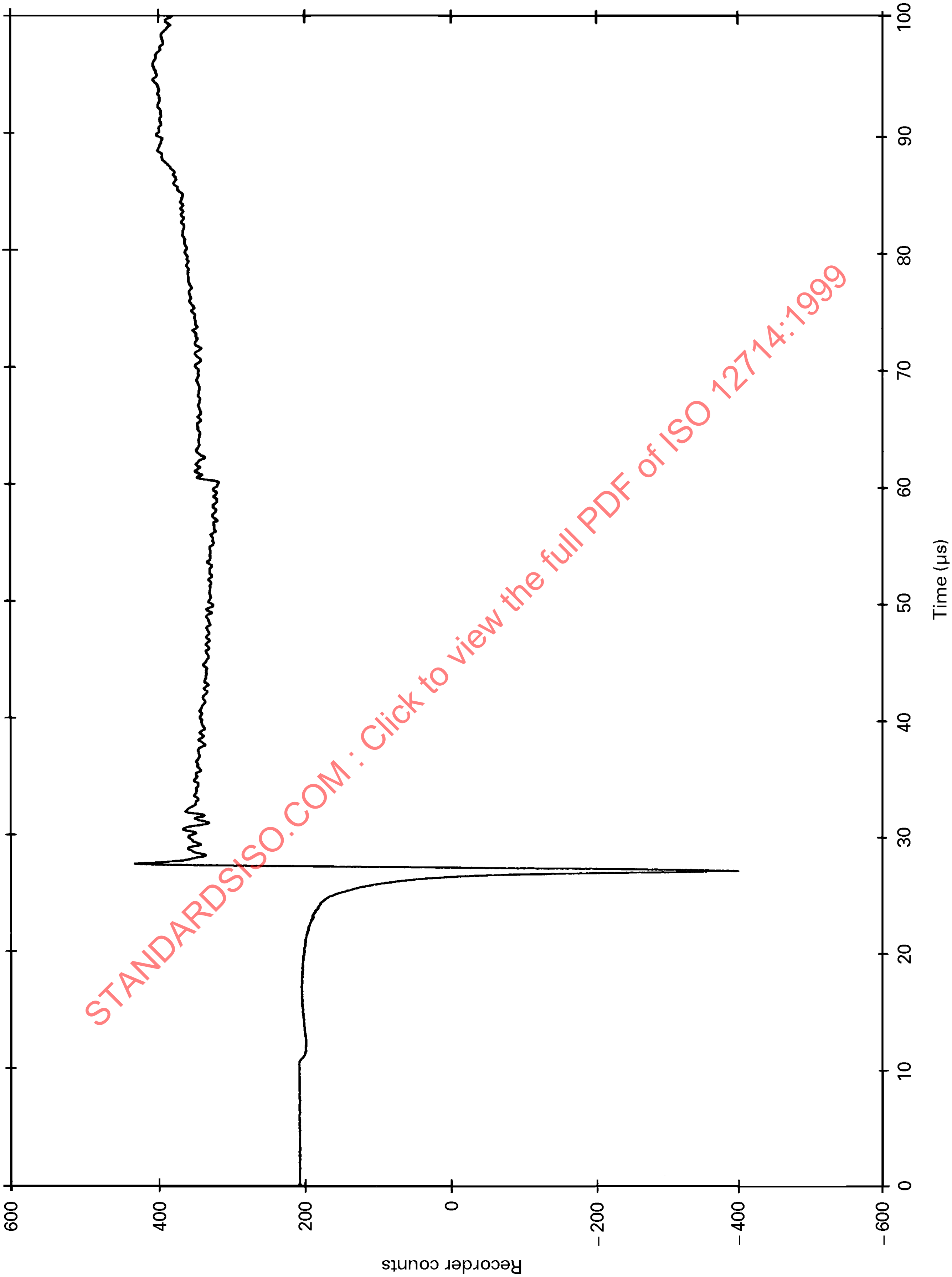


Figure 2 — Waveform of the reference sensor from a test performed with the prototype secondary calibration system

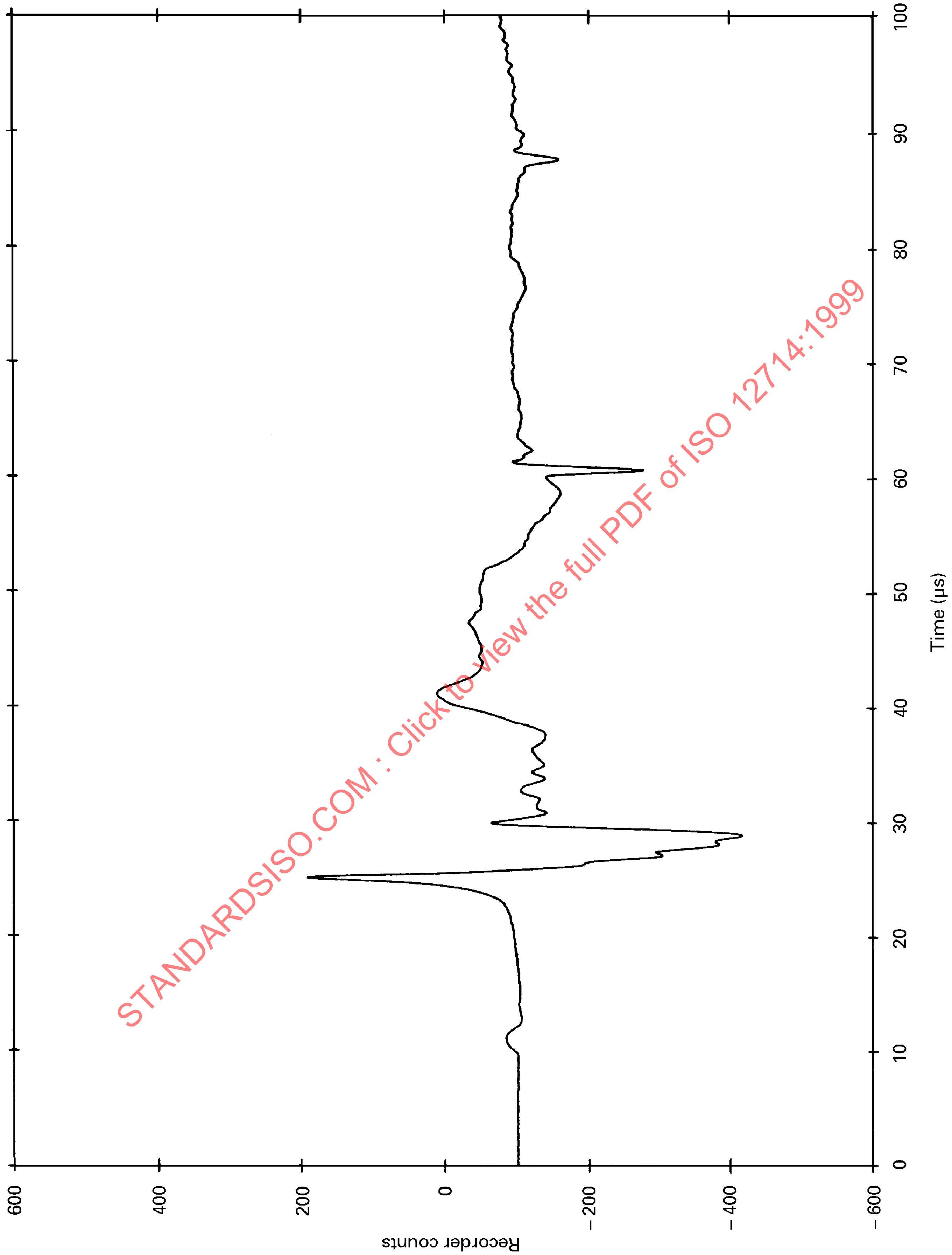


Figure 3 — Waveform of the sensor under test, recorded simultaneously with the reference sensor waveform of Figure 2

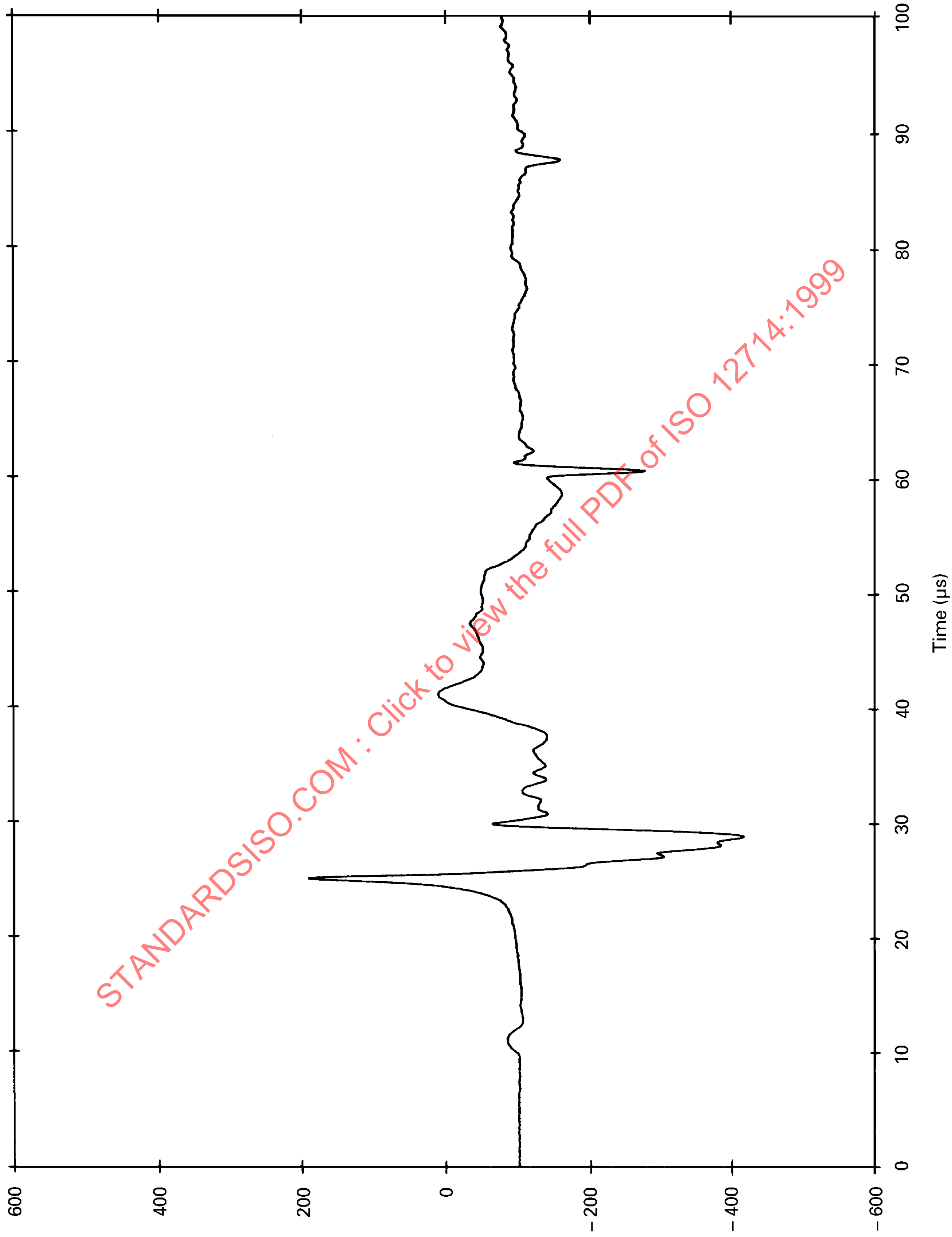


Figure 4 — Magnitude of the frequency response of the sensor under test, derived from the data of Figures 2 and 3

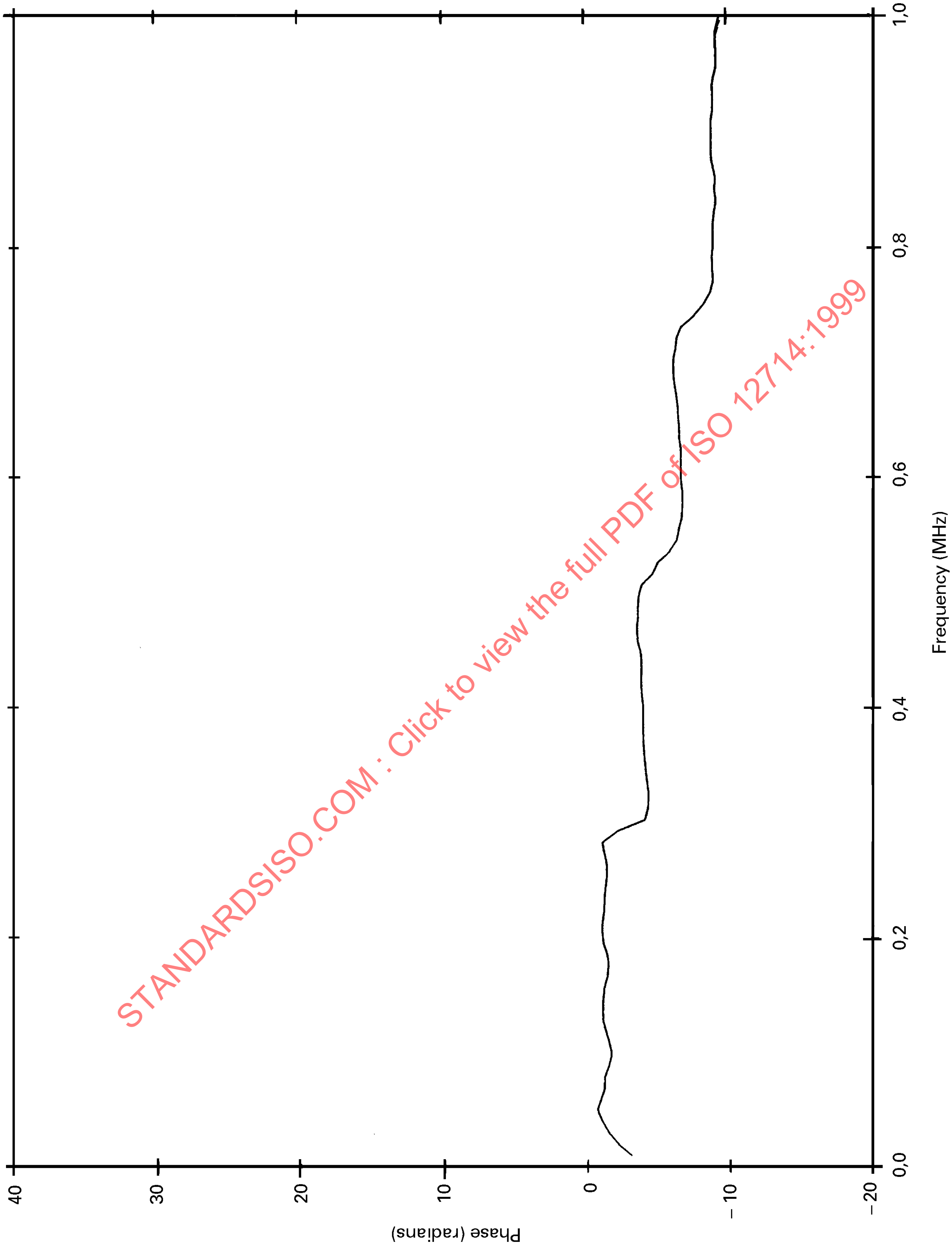
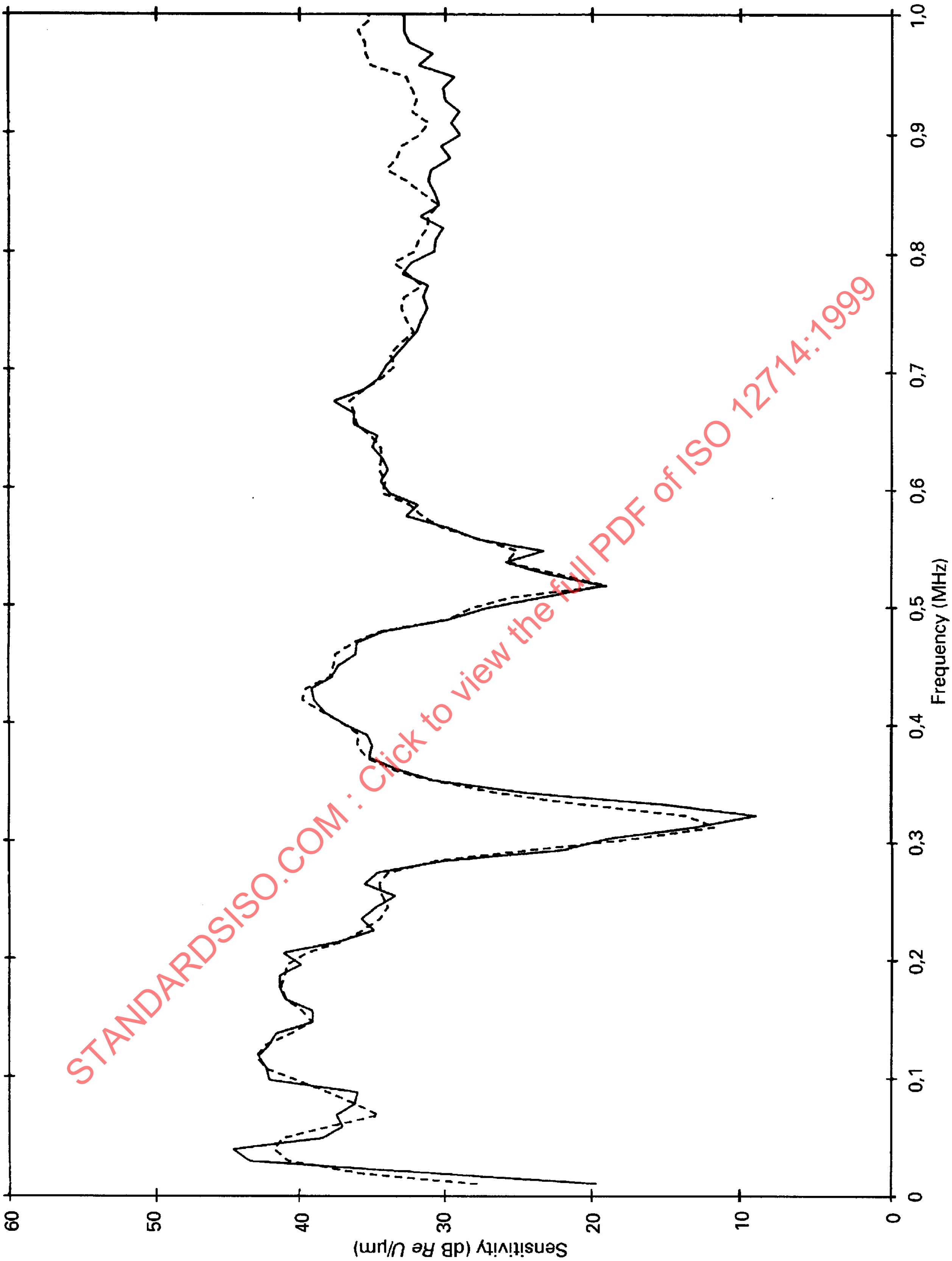


Figure 5 — Phase of the frequency response of the sensor under test, derived from the data of Figures 2 and 3



NOTE Worst case errors are 3 dB, while most of the data agree to within 1 dB.

Figure 6 — Comparison of primary and secondary calibration results for a sensor with nominal diameter 12,7 mm