
**Hydraulic fluid power — Determination of
fluid-borne noise characteristics of
components and systems —**

Part 2:

**Measurement of speed of sound in a fluid in
a pipe**

*Transmissions hydrauliques — Évaluation des caractéristiques du bruit
liquidien des composants et systèmes —*

*Partie 2: Mesurage de la vitesse du son émis dans un fluide dans une
tuyauterie*



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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.

Attention is drawn to the possibility that some of the elements of this part of ISO 15086 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 15086-2 was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 8, *Product testing*.

ISO 15086 consists of the following parts, under the general title *Hydraulic fluid power — Determination of fluid borne noise characteristics of components and systems*:

- *Part 1: Introduction*
- *Part 2: Measurement of the speed of sound in a fluid in a pipe*

Annexes A, B and C form a normative part of this part of ISO 15086. Annexes D and E are for information only

Introduction

In hydraulic fluid power systems, power is transmitted and controlled through a liquid under pressure within an enclosed circuit. During the process of converting mechanical power into hydraulic fluid power, flow and pressure fluctuations and structure-borne vibrations are generated.

Hydro-acoustical characteristics of hydraulic components can be measured with acceptable accuracy if the speed of sound in the fluid is precisely known.

The measurement technique for determining the speed of sound in a pipe, as described in this part of ISO 15086, is based upon the application of plane wave transmission line theory to the analysis of pressure fluctuations in rigid pipes [1].

Two different measurement approaches are presented, namely the use of:

- three pressure transducers in a pipe,
- acoustic antiresonance in a closed-end pipe system.

The three-pressure-transducer method should be used at any time when the speed of sound is to be measured under the effective working conditions in a system.

The antiresonance method should be used to produce a table of speed-of-sound data as a function of mean pressure and temperature for a particular fluid.

Hydraulic fluid power — Determination of fluid borne noise characteristics of components and systems —

Part 2: Measurement of the speed of sound in a fluid in a pipe

1 Scope

This part of ISO 15086 describes the procedure for the determination of the speed of sound in a fluid enclosed in a pipe, by measurements from pressure transducers mounted in the pipe.

This part of ISO 15086 is applicable to all types of hydraulic circuit operating under steady state conditions, irrespective of size, for pressure pulsations over a frequency range from 25 Hz to 2 500 Hz.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 15086. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 15086 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 1000:1992, *SI units and recommendations for the use of their multiples and of certain other units*.

ISO 1219-1:1991, *Fluid power systems and components — Graphic symbols and circuit diagrams — Part 1: Graphic symbols*.

ISO 5598:1985, *Fluid power systems and components — Vocabulary*.

3 Terms and definitions

For the purposes of this part of ISO 15086, the terms and definitions given in ISO 5598 and the following apply.

3.1

flow ripple

fluctuating component of flowrate in a hydraulic fluid, caused by interaction with a flow ripple source within the system

3.2

pressure ripple

fluctuating component of pressure in a hydraulic fluid, caused by interaction with a flow ripple source within the system

3.3

fundamental frequency

lowest frequency of pressure ripple measured by the frequency-analysis instrument

**3.4
harmonic**

sinusoidal component of the pressure ripple or flow ripple occurring at an integer multiple of the fundamental frequency

NOTE A harmonic may be represented by its amplitude and phase, or alternatively by its real and imaginary parts.

**3.5
hydraulic noise generator**

hydraulic component generating flow ripple and consequently pressure ripple in the circuit

**3.6
measurement pipe**

pipe in which the pressure transducers are mounted

**3.7
impedance**

complex ratio of the pressure ripple to the flow ripple occurring at a given point in a hydraulic system and at a given frequency

**3.8
entry impedance.**

impedance at the entry of a pipe or piping system

**3.9
first acoustic antiresonance frequency**

lowest frequency at which the magnitude of the entry impedance of the measurement pipe is at a minimum

4 Symbols and subscripts

4.1 Symbols

A, A', a, B, B', b	Frequency-dependent wave propagation coefficients (complex numbers)
c	Acoustic velocity in the fluid
d	Internal diameter of pipe
f	Frequency of the wave pulsation harmonic
f_i	Vector of frequencies at which measurements are conducted
f_0	First acoustic antiresonance frequency (in hertz)
H	Transfer function (complex number) between two pressure transducer signals after calibration correction
H'	Transfer function (complex number) between two pressure transducer signals under calibration
H^*	Transfer function (complex number) between two pressure transducer signals
j	$\sqrt{-1}$
L	Distance between transducers 1 and 2 (Method 1)
L'	Distance between transducers 2 and 3 (Method 1)

l	Distance between pressure transducers (Method 2)
P_1	Pressure ripple of transducer PT1 (complex number)
P_2	Pressure ripple of transducer PT2 (complex number)
P_3	Pressure ripple of transducer PT3 (complex number)
$Q_{1 \rightarrow 2}$	Flow ripple at location 1, from 1 to 2 (complex number)
$Q_{2 \rightarrow 1}$	Flow ripple at location 2, from 2 to 1 (complex number)
$Q_{2 \rightarrow 3}$	Flow ripple at location 3, from 2 to 3 (complex number)
S_i	Coherence function corresponding to measurement frequencies, f_i
ε	Error (complex number)
$\bar{\varepsilon}$	Conjugate of complex number ε (complex number)
ε_x	Real part of ε
ε_y	Imaginary part of ε
ρ	Density of fluid
ν	Kinematic viscosity of fluid
ω	$2\pi f$

NOTE $H, H', H^*, P_1, P_2, P_3, Q_{1 \rightarrow 2}, Q_{2 \rightarrow 1}, Q_{2 \rightarrow 3}$ are all frequency-dependent terms and hence are designated by upper-case letters.

Units used in this part of ISO 15086 are in accordance with ISO 1000.

Graphical symbols are in accordance with ISO 1219-1 unless otherwise stated.

4.2 Subscripts

O	Index for old value
N	Index for new value

5 Instrumentation

5.1 Static measurements

The instruments used to measure

- a) mean flow (Method 1 only);
- b) mean fluid pressure;
- c) fluid temperature;

shall meet the requirements for "industrial class" accuracy of measurement, i.e. class C as given in annex B.

5.2 Dynamic measurements

The instruments used to measure pressure ripple shall have the following characteristics:

- a) resonant frequency ≥ 30 kHz;
- b) linearity $\geq \pm 1$ %;
- c) preferably include acceleration compensation.

The instruments need not respond to steady-state pressure. It may be advantageous to filter out any steady-state signal component using a high-pass filter. This filter shall not introduce an additional amplitude or phase error exceeding 0,5 % or 0,5° respectively of the current measurement.

5.3 Frequency analysis of pressure ripple

A suitable instrument shall be used to measure the amplitude and phase of the pressure ripple.

The instrument shall be capable of measuring the pressure ripple from the pressure transducers such that, for a particular harmonic, the measurements from each transducer are performed simultaneously and synchronised in time with respect to each other.

The instrument shall have an accuracy and resolution for harmonic measurements of

- a) amplitude within $\pm 0,5$ %;
- b) phase within $\pm 0,5^\circ$;
- c) frequency within $\pm 0,5$ %;

over the frequency range from 25 Hz to 2 500 Hz.

5.4 Uncertainty

Compliance with the above specification will result in an uncertainty in measurement of speed of sound of less than ± 3 %.

6 Hydraulic noise generator

6.1 General

Any type of hydraulic noise generator may be used, provided that sufficient pressure ripple is created at the pressure transducers to allow accurate measurements to be taken.

EXAMPLE Pumps and motors create a pressure ripple consisting essentially of many harmonics of the fundamental frequency. In these cases, the fundamental frequency is equal to the product of the shaft rotational frequency and the number of gear teeth, vanes or pistons, etc. (as appropriate to the machine employed).

Suitable alternatives include:

- an auxiliary valve with a rotating spool allowing flow to pass to the return line over part of its rotation;
- an electrohydraulic servo-valve driven by a frequency generator.
- The servo-valve may be operated with a white noise signal in order to obtain significant pressure ripple measurements at each frequency of interest.

6.2 Generator vibration

If necessary, the measurement pipe should be structurally isolated from the generator to minimize vibration.

7 Test conditions

7.1 General

The required operating conditions shall be maintained throughout each test within the limits specified in Table 1.

7.2 Fluid temperature

The temperature of the fluid shall be that measured at the entry to the measurement pipe.

7.3 Fluid density and viscosity

The density and viscosity of the fluid shall be known to an accuracy within the limits specified in Table 2.

7.4 Mean fluid pressure

The mean fluid pressure of the fluid shall be that measured at the entry to the measurement pipe.

7.5 Mean flow measurement

The mean flow shall be measured down-stream of the measurement pipe (Method 1 only).

Table 1 — Permissible variations in tests conditions

Test parameter	Permissible variation
Mean flow	$\pm 2 \%$
Mean pressure	$\pm 2 \%$
Temperature	$\pm 2 \text{ }^\circ\text{C}$

Table 2 — Required accuracy of fluid property data

Property	Required accuracy
Density	$\pm 2 \%$
Viscosity	$\pm 5 \%$

8 Test rig

8.1 General

If, at any test condition, the pressure ripple amplitudes are too small for satisfactory frequency-spectrum analysis to be performed, an alternative noise generator shall be selected.

The pressure transducers shall be mounted such that their diaphragms are flush, within $\pm 0,5 \text{ mm}$, with the inner wall of the pipe.

Two alternative specifications for the measurement pipe and transducer position are given, in accordance with the method employed.

8.2 Thermal insulation

Temperature shall be measured at both ends of the measurement pipe. The difference in temperature between the two ends of the measurement pipe shall not exceed 2 °C at any test condition. If necessary, sufficient thermal lagging shall be applied to the measurement pipe to enable this requirement to be met.

8.3 Method 1: Three-transducer method

8.3.1 This method is suitable when the velocity of sound is to be measured at the same time as other hydro-acoustical characteristics of hydraulic components, such as impedance, source flow ripple or transfer matrix coefficients. The measurement pipe shall be installed at the place in the test system where measurement of the speed of sound is needed. Several measurement pipes may be used simultaneously, if required.

The measurement pipe shall be uniform and straight. Its internal diameter shall be between 80 % and 120 % of the diameter of the pipes, or component ports, to which it is connected. The pipe should be supported in such a manner that vibration is minimized.

For cases where other hydro-acoustic properties are not being measured simultaneously, a pump (and if necessary, a hydraulic noise generator) shall be mounted at one end of the measurement pipe. The other end shall be terminated by a loading valve without free-moving internal parts, such as a needle valve.

Mean pressure shall be measured at the upstream end of the measurement pipe.

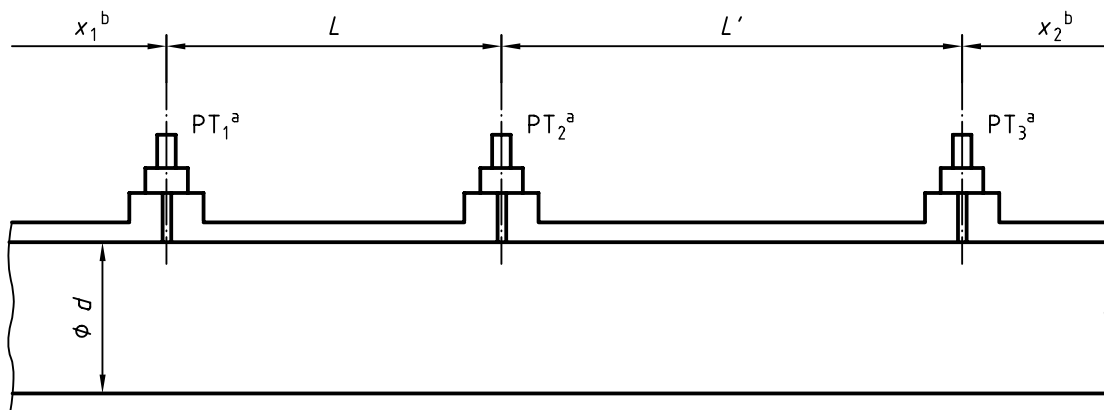
8.3.2 Three pressure transducers are required for Method 1, configured as shown in Figure 1. The transducer spacing shall be selected according to the standard specifications of hydro-acoustical measurements to be carried out simultaneously. Otherwise, the distances L and L' between the pressure transducers shall be as specified in Table 3.

Table 3 — Spacing of transducers: Method 1

L	330 mm ± 2 mm
L'	470 mm ± 2 mm

The distance between each end of the measurement pipe and the nearest pressure transducer shall be at least $10d$, where d is the internal diameter of the pipe. The distances L and L' between the transducers, as shown in Figure 1, shall be measured to an accuracy of ± 0,5 mm.

No other components shall be connected between the inlet port and outlet port of the measurement pipe.



- a Pressure transducers.
- b Distances to end of measurement pipe, $x_1 \geq 10d$ and $x_2 \geq 10d$.

Figure 1 — Arrangement of three pressure transducers in measurement pipe

8.4 Method 2: Antiresonance method

8.4.1 This method can be used to produce a data chart of the speed of sound for a particular fluid. Due to the pressure resonances that are created in the system, this method is not appropriate when other hydro-acoustical measurements are to be undertaken.

8.4.2 An appropriate test rig is presented schematically in Figure 2 a). The loading valve shall not contain free-moving parts. A needle valve is an example of a suitable loading valve. The measurement pipe takes the form of a closed-end side-branch line connected to the pump/pipe/loading-valve circuit as shown. It is important that the fluid in the measurement pipe is at as uniform a temperature as possible, and does not contain gas bubbles. To achieve these objectives, the measurement pipe is terminated by a bleed valve. A needle valve is an example of a suitable bleed valve. Prior to measurements being taken, the bleed valve is opened for a period of time sufficient to flush the pipe of gas bubbles and to stabilize temperature. The measurement pipe shall be orientated downwards with the bleed valve below the level of the through-flow pipe to prevent the trapping of air in the measurement pipe during testing. It is important that the bleed valve does not introduce significant extra volume at the end of the line when the valve is in the closed position.

The pressure transducers, PT_1 and PT_2 in Figure 2 a), are located at each end of the measurement pipe. It is essential that transducer PT_2 is mounted as closely as possible to the end of the pipe. Moreover, the location of transducer PT_1 should be as close as possible to the point where the measurement pipe is connected to the main circuit. Figure 2 b) provides an example of how these requirements may be achieved. In this example, the measurement pipe is terminated by a purpose-built housing which contains the needle valve assembly.

The hydraulic components necessary to obtain the appropriate test conditions may, inherently, generate sufficient pressure pulsation levels to allow satisfactory frequency-spectrum analysis to be performed. Should this not be the case, a separate hydraulic noise generator shall be connected to the circuit, as shown in Figure 2 a).

In order to maximize the pressure pulsation levels, the distance between the pump (or the noise generator if in use) and the loading valve should not be greater than one-tenth of the measurement pipe length.

8.4.3 The measurement pipe shall be a uniform, rigid, straight metal pipe. The internal diameter of the pipe shall be between 50 % and 100 % of the diameter of the line where it is connected. This pipe shall be supported in such a manner that pipe vibration is minimized.

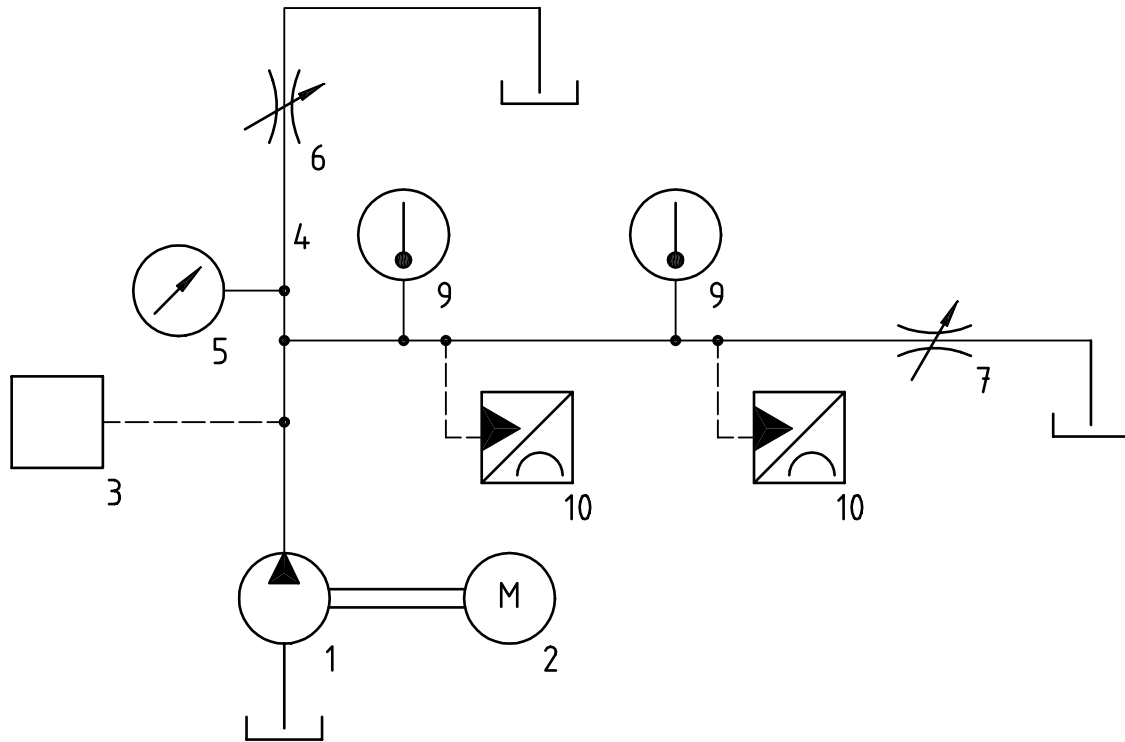
The distance, l , between the pressure transducers shall be defined according to the first acoustic antiresonance frequency f_0 by equation (1).

$$l = \frac{1}{4f_0} \sqrt{\frac{B \times 10^6}{\rho}} \quad (1)$$

The effective bulk modulus B can be estimated using manufacturer's data for the fluid consistent with the operating condition of the tests. An accurate value is not required.

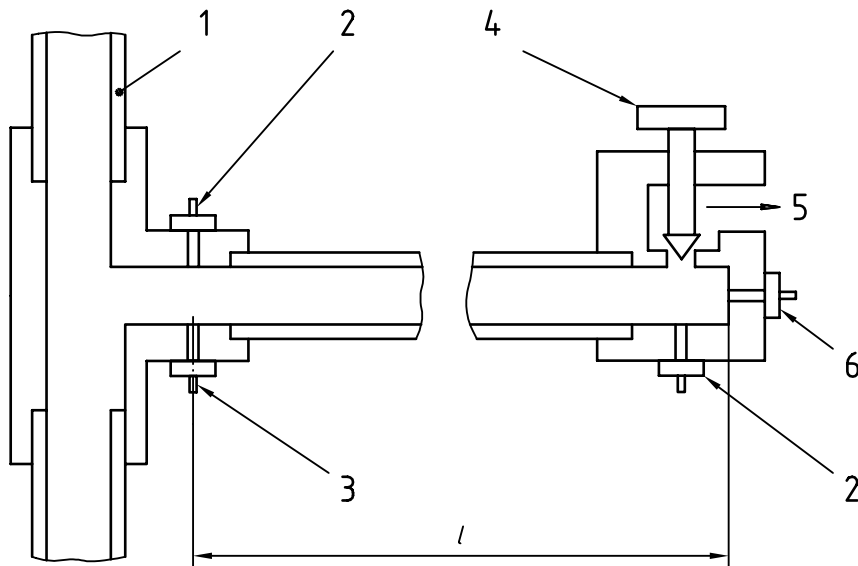
The frequency f_0 should be chosen in the range 100 Hz to 200 Hz.

The distance between the pressure transducers shall be measured to an accuracy of $\pm 0,5$ mm.



- Key**
- | | |
|---------------------------------------|---------------------------|
| 1 Pump | 6 Loading valve |
| 2 Electric motor | 7 Bleed valve |
| 3 Hydraulic noise generator (if used) | 8 Measurement pipe |
| 4 Through-flow pipe | 9 Temperature transducers |
| 5 Pressure gauge | 10 Pressure transducers |

a) Circuit layout



- Key**
- | | |
|---------------------------------------|---------------------------------------|
| 1 Through-flow pipe | 4 Needle valve adjustment |
| 2 Temperature transducer | 5 To reservoir |
| 3 Pressure transducer PT ₁ | 6 Pressure transducer PT ₂ |

b) Example of transducer locations and bleed valve mounting

NOTE Graphical symbols are for illustration purposes and do not conform to ISO 1219-1.

Figure 2 — Typical antiresonance test arrangement

8.5 Calibration of pressure transducers

Calibration of pressure transducers and signal conditioning is necessary. Perform relative calibration by mounting the pressure transducers in a common block such that they measure the same pressure ripple. Construct this common block such that the pressure transducers are at the same axial position and no more than one internal diameter of the measurement pipe apart.

Measure the amplitude and phase relationship between the pressure transducers for a range of frequencies spanning the complete range of interest with one transducer used as a reference. For piezoresistive transducers, the reference transducer can be calibrated statically using, for example, a deadweight testing machine.

If piezoelectric transducers and charge amplifiers are employed, a calibrated piezoresistive transducer may be used as a reference for dynamic calibration purposes.

If the amplitude or phase difference between the transducers exceeds 1 % or 0,5° respectively, correct for the differences in the analysis of the test data (see 9.3 and 10.3). Record the transfer functions.

$$H'_{12} = \frac{P_1}{P_2}$$

and

$$H'_{32} = \frac{P_3}{P_2}$$

obtained during calibration.

9 Test procedure for Method 1

9.1 Prior to the commencement of tests, operate the hydraulic system for a sufficient period of time to purge air from the system and to stabilize all variables, including fluid condition, to within the limits given in Table 1. If a speed of sound test is to be performed at the same time as other hydro-acoustical measurements, conditions to the standard relevant to those measurements can be used.

9.2 Take the ensemble average of at least 16 time-series pressure transfer functions

$$H_{12}^* = \frac{P_1}{P_2} \text{ and } H_{32}^* = \frac{P_3}{P_2}$$

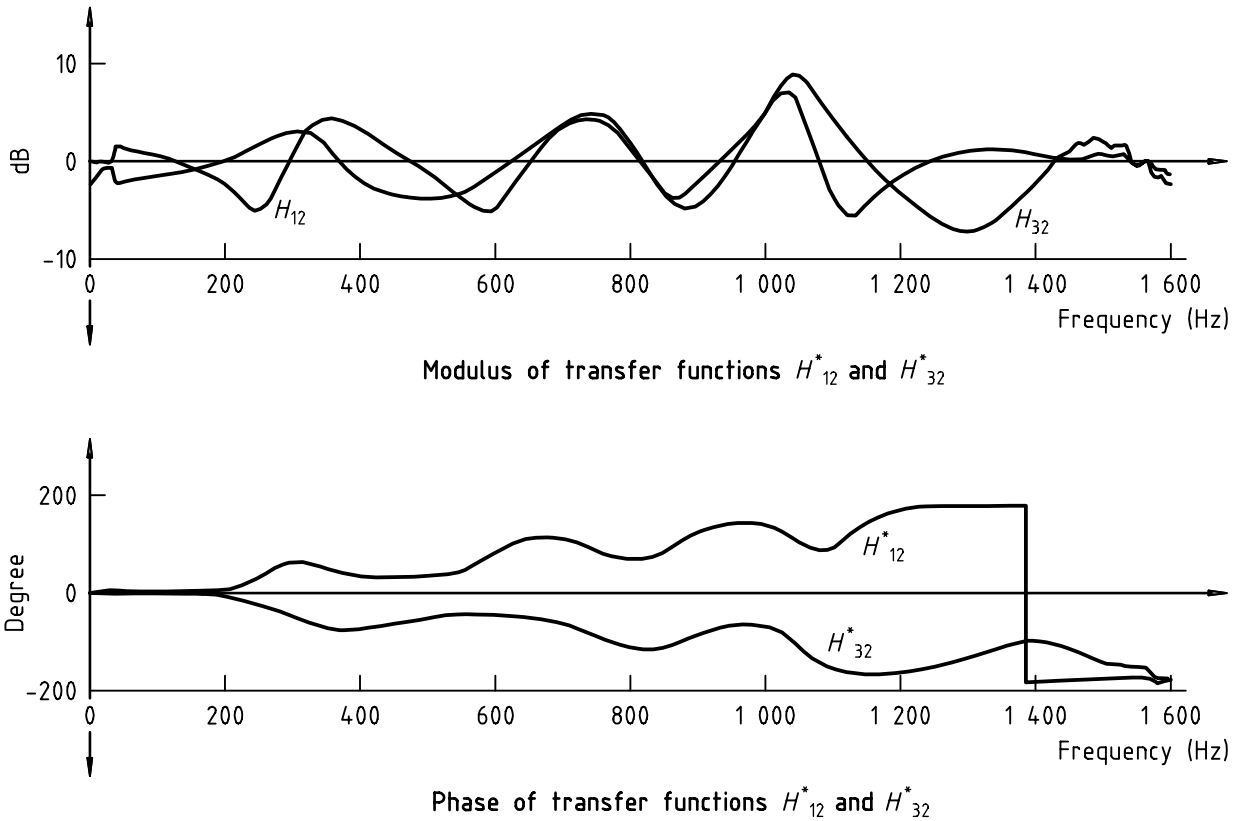
and calculate the coherence function S_i at each frequency f_i over the frequency range. Typical examples of the transfer functions H_{12}^* and H_{32}^* are given, for the case of broad-band excitation, in Figure 3.

9.3 Perform the correction of the ensemble-averaged transfer functions H_{12} and H_{32} using the transfer functions obtained from the calibration procedure H'_{12} and H'_{32} (see 8.5) using equations (2) and (3).

$$H_{12} = \frac{H^*_{12}}{H'_{12}} \tag{2}$$

$$H_{32} = \frac{H^*_{32}}{H'_{32}} \tag{3}$$

If correction is not necessary (see 8.5), then $H_{12} = H^*_{12}$ and $H_{32} = H^*_{32}$.



Key

- 1 Modulus of transfer functions H^*_{12} and H^*_{32}
- 2 Frequency (Hz)
- 3 Degree
- 4 Phase of transfer functions H^*_{12} and H^*_{32}

Figure 3 — Typical example of transfer functions H^*_{12} and H^*_{32}

9.4 Calculate the speed of sound for each frequency having an associated coherence function S_i greater than 0,95 as described in C.1. The S_i function is always a positive number less than or equal to 1. The least-squares error procedure given in C.1 allows the speed of sound, averaged over the frequency range investigated, to be calculated.

9.5 Calculate the mean fluid velocity by dividing the mean flow by the internal cross-sectional area of the measurement pipe. If the mean fluid velocity is greater than 5 % of any speed of sound measurement, then the method is invalid and results shall not be reported.

10 Test procedure for Method 2

10.1 Prior to the commencement of a series of tests, operate the hydraulic system and noise generator (if included) for a sufficient period of time to purge air from the system and to stabilize all variables, including fluid condition, to within the limits given in Table 1. Particular attention should be given to obtaining a representative fluid characteristic, especially the bulk modulus.

The bleed valve should be fully open to allow flow through the measurement pipe during this stabilization period. The restrictor valve downstream of the bleed valve should be adjusted to create a mean pressure approximately 0,5 MPa below the desired test pressure during this phase. Immediately before pressure transducer measurements are taken, the bleed valve should be closed and, if necessary, the mean pressure re-established through adjustment of the loading valve.

Warning — No safety valves are included in the system. Personnel performing tests should exercise great care to ensure that excessive and dangerous pressures are not created when adjusting restrictor valves.

10.2 Take the ensemble average of at least 16 time-series pressure transfer functions.

$$H_{12}^* = \frac{P_1}{P_2}$$

10.3 Perform the correction of the measured transfer function H_{21}^* using the transfer function obtained from the calibration procedure of transducers PT_1 and PT_2 , $H'_{21} = P_2/P_1$ (see 8.5) using equation (4).

$$H_{21} = \frac{H_{21}^*}{H'_{21}} \quad (4)$$

If correction is not necessary (see 8.5), then $H_{21} = H_{21}^*$.

10.4 Identify and record the frequencies for which the transfer function H_{21} is a maximum. Calculate the speed of sound as described in C.3.

11 Test report

11.1 General information

The test report shall contain the following general information.

- a) Name and address of organization performing the test;
- b) name of persons performing the test;
- c) reference specifications of fluid tested;
- d) date and place of tests;
- e) conformance statement (see clause 12).

11.2 Test data

The test report shall contain the following test data.

- a) Mounting and installation conditions of the measurement pipe:
 - 1) description of measurement pipe (length; internal diameter; wall thickness; material);
 - 2) description of test rig (only for Method 2);
 - 3) nature and characteristics of hydraulic circuit and details of any vibration and thermal insulation treatment;
- b) test method adopted (Method 1 or Method 2);
- c) instrumentation:
 - 1) class of measurement;
 - 2) details of equipment used for pressure ripple measurements, including type, serial number and manufacturer;
 - 3) bandwidth of frequency analyser;
 - 4) overall frequency response of instrumentation system and date and method of last calibration;
 - 5) method of calibration of pressure transducers and date and place of last calibration.

- d) operating conditions of test:
- 1) type of fluid;
 - 2) kinematic viscosity (in centistokes; 1 cSt = 1 mm²/s);
 - 3) fluid density [in kilograms per cubic metre (kg/m³)];
 - 4) fluid temperature (in degrees Celsius);
 - 5) mean pressure [in megapascals (MPa)];
 - 6) mean flow in rigid pipe for Method 1 [in cubic metres per second (m³/s)].

11.3 Test results

The test report shall contain the following test results.

- a) The speed of sound [in metres per second (m/s)];
- b) Temperature at the entry to the measurement pipe (in degrees Celsius) and mean pressure [in megapascals (MPa)] of the fluid associated with the respective value of speed of sound.

12 Identification statement (Reference to this part of ISO 15086)

Use the following statement in tests reports, catalogues and sales literature when electing to comply with this part of ISO 15086:

"Speed of sound determined in accordance with ISO 15086-2, Hydraulic fluid power — Determination of fluid-borne noise characteristics of components and systems — Part 2: Measurement of the speed of sound in a fluid in a pipe"

Annex A (normative)

Errors and classes of measurement of mean value

Depending on the accuracy required, carry out the tests to one of the three classes of measurement, A, B or C.

The procedures described assume that measurements of the mean value of variables are made to class C in accordance with Table A.1. In special cases, more precise measurement can be made using class A or B by agreement with the parties concerned. Attention is drawn to the fact that class A and B measurements require more accurate apparatus and methods, which increases the cost of such tests.

Table A.1 — Permissible systematic errors of measuring instrument determined during calibration

Class of measurement	Mean flow %	Mean pressure %	Temperature °C
A	± 0,5	± 0,5	± 0,5
B	± 1,5	± 1,5	± 1,0
C	± 2,5	± 2,5	± 2,0

NOTE The percentage limits given in Table A.1 are of the value of the quantity being measured and not of the maximum values of the test or the maximum reading of the instrument.

Annex B (normative)

Errors and classes of dynamic measurement

Depending of the accuracy required, carry out the tests to one of the three classes of dynamic measurement, A, B or C.

The procedure described assumes that measurements of the instantaneous value of the variable pressure is made to class A in accordance with Table B.1.

Table B.1 — Permissible systematic errors of measuring instruments as determined during calibration

Class of dynamic measurements	Instantaneous pressure %
A	$\pm 1,5$
B	$\pm 3,0$
C	$\pm 5,0$

NOTE The percentage limits given in Table B.1 are of the value of the quantity being measured, and not of the maximum values of the test or the maximum reading of the instrument.

Annex C (normative)

Data reduction algorithms

C.1 Introduction

The experimentally measured harmonic pressure ripple or transfer function data need to be mathematically processed to evaluate the speed of sound. Because of the complexity of the analysis, the data processing is preferably carried out using a frequency analyser, and a digital computer.

This annex describes the mathematical techniques involved in the processing of the data.

C.2 The three-transducer method

C.2.1 Basis of the method

This method requires the simultaneous measurement of three pressure ripples at different places in a constant-diameter rigid pipe.

The work of Lallement [1] shows that the flow ripple into a section of constant-diameter pipe is a linear combination of pressure ripples at that point and another point in the same pipe.

$$Q_1 \rightarrow 2 = A P_1 + B P_2 \quad (\text{C.1})$$

$$Q_2 \rightarrow 1 = A P_2 + B P_1$$

$$A = \frac{\pi d^2 \omega}{4c} \frac{1}{(a - jb)} \coth \left[j(a - jb) \frac{L}{c} \right] \quad (\text{C.2})$$

$$B = \frac{\pi d^2 \omega j}{4c(a - jb) \sin \left[(a - jb) \frac{L}{c} \right]} \quad (\text{C.3})$$

$$a = \left(\omega + \sqrt{\frac{2\omega v}{d^2}} \right) \quad (\text{C.4})$$

$$b = \left(\frac{4v}{d^2} + \sqrt{\frac{2\omega v}{d^2}} \right) \quad (\text{C.5})$$

Applying equation (C.1) to a rigid pipe equipped with three pressure transducers PT₁, PT₂ and PT₃, set at distances *L* and *L'* respectively, yields:

$$Q_2 \rightarrow 1 = A P_2 + B P_1 \quad (\text{C.6})$$

$$Q_2 \rightarrow 3 = A' P_2 + B' P_3 \quad (\text{C.7})$$

Just upstream of pressure transducer PT₂ we get:

$$Q_2 \rightarrow 1 + Q_2 \rightarrow 3 = 0 \tag{C.8}$$

$$(A + A') P_2 + B P_1 + B' P_3 = 0 \tag{C.9}$$

$$\text{Thus } 1 + \frac{B}{A + A'} \left(\frac{P_1}{P_2} \right) + \frac{B'}{A + A'} \left(\frac{P_3}{P_2} \right) = 0 \tag{C.10}$$

This equation is verified theoretically at any frequency if the speed of sound is known exactly.

In practice, with measured pressure-pulsation transfer functions, the result is non-zero. Hence, (C.10) can be written:

$$1 + \frac{B}{A + A'} (H_{12}) + \frac{B'}{A + A'} (H_{32}) = \varepsilon$$

Substituting from C.2, C.3, C.4 and C.5 and rearranging yields (C.11), thus:

$$\varepsilon = H_{12} \sin \left[\frac{L'}{c} (a - jb) \right] + H_{32} \sin \left[\frac{L}{c} (a - jb) \right] - \sin \left[\frac{L + L'}{c} (a - jb) \right] \tag{C.11}$$

C.2.2 Theory of the speed of sound calculation

The speed of sound is established by using a least squares error procedure to minimize the total error E :

$$E = \sum_1^N \varepsilon \bar{\varepsilon}$$

The total error E is the sum of the squares of the amplitude errors ε at each frequency of the spectrum.

The minimum of E is obtained when:

$$\frac{\partial E}{\partial c} = 0$$

$$\text{Thus } \frac{\partial \left(\sum \varepsilon \bar{\varepsilon} \right)}{\partial c} = \sum \frac{\partial (\varepsilon \bar{\varepsilon})}{\partial c} = \sum \varepsilon_N \frac{\partial \bar{\varepsilon}}{\partial c} + \sum \bar{\varepsilon}_N \frac{\partial \varepsilon}{\partial c} = 0 \tag{C.12}$$

Using the first-order Newton formula of interpolation, we get:

$$\varepsilon_O - \varepsilon_N = (c_O - c_N) \frac{\partial \varepsilon}{\partial c} \tag{C.13}$$

and

$$\bar{\varepsilon}_O - \bar{\varepsilon}_N = (c_O - c_N) \frac{\partial \bar{\varepsilon}}{\partial c} \tag{C.14}$$

Substituting ε_N and $\bar{\varepsilon}_N$ from (C.13) and (C.14) in equation (C.12):

$$\sum \varepsilon_O \frac{\partial \bar{\varepsilon}}{\partial c} - \sum (c_O - c_N) \frac{\partial \varepsilon}{\partial c} \frac{\partial \bar{\varepsilon}}{\partial c} + \sum \bar{\varepsilon}_O \frac{\partial \varepsilon}{\partial c} - \sum (c_O - c_N) \frac{\partial \varepsilon}{\partial c} \frac{\partial \bar{\varepsilon}}{\partial c} = 0 \tag{C.15}$$

$$2 \sum (c_O - c_N) \frac{\partial \varepsilon}{\partial c} \frac{\partial \bar{\varepsilon}}{\partial c} = \sum \varepsilon_O \frac{\partial \bar{\varepsilon}}{\partial c} + \sum \bar{\varepsilon}_O \frac{\partial \varepsilon}{\partial c} \quad (\text{C.16})$$

$$\varepsilon_O \frac{\partial \bar{\varepsilon}}{\partial c} = \left(\varepsilon_O \frac{\partial \varepsilon}{\partial c} \right) \quad (\text{C.17})$$

$$2 \sum (c_O - c_N) \frac{\partial \varepsilon}{\partial c} \frac{\partial \bar{\varepsilon}}{\partial c} = 2 \operatorname{Re} \left[\sum \bar{\varepsilon}_O \frac{\partial \bar{\varepsilon}}{\partial c} \right] = 2 \operatorname{Re} \left[\sum \varepsilon_O \frac{\partial \bar{\varepsilon}}{\partial c} \right] \quad (\text{C.18})$$

The iterative formula for speed of sound calculation is:

$$c_N = c_O - \frac{\operatorname{Re} \left[\sum \bar{\varepsilon}_O \frac{\partial \bar{\varepsilon}}{\partial c} \right]}{\sum \frac{\partial \varepsilon}{\partial c} \frac{\partial \bar{\varepsilon}}{\partial c}} \quad (\text{C.19})$$

This iterative procedure should be terminated when $\frac{c_N - c_O}{c_N} = 0,000 1$

C.2.3 Detailed calculations

From (C.11) we can obtain

$$\frac{\partial \varepsilon}{\partial c} = \frac{a - jb}{c^2} \left\{ -\frac{P_1}{P_2} L' \cos \left[\frac{L'}{c} (a - jb) \right] - \frac{P_3}{P_2} L \cos \left[\frac{L}{c} (a - jb) \right] + (L + L') \cos \left[\frac{L + L'}{c} (a - jb) \right] \right\} \quad (\text{C.20})$$

The expressions for ε and $\frac{\partial \varepsilon}{\partial c}$ are complex numbers, thus:

$$\varepsilon = \varepsilon_x + j \varepsilon_y \quad (\text{C.21})$$

and

$$\frac{\partial \varepsilon}{\partial c} = \frac{\partial \varepsilon_x}{\partial c} + j \frac{\partial \varepsilon_y}{\partial c} \quad (\text{C.22})$$

We get:

$$\bar{\varepsilon} = \varepsilon_x - j \varepsilon_y \quad (\text{C.23})$$

$$\frac{\partial \bar{\varepsilon}}{\partial c} = \frac{\partial \varepsilon_x}{\partial c} - j \frac{\partial \varepsilon_y}{\partial c} \quad (\text{C.24})$$

$$\bar{\varepsilon} \frac{\partial \varepsilon}{\partial c} = \varepsilon_x \frac{\partial \varepsilon_x}{\partial c} + \varepsilon_y \frac{\partial \varepsilon_y}{\partial c} + j \left[\varepsilon_x \frac{\partial \varepsilon_y}{\partial c} - \varepsilon_y \frac{\partial \varepsilon_x}{\partial c} \right] \quad (\text{C.25})$$

$$\frac{\partial \varepsilon}{\partial c} \frac{\partial \bar{\varepsilon}}{\partial c} = \left(\frac{\partial \varepsilon_x}{\partial c} \right)^2 + \left(\frac{\partial \varepsilon_y}{\partial c} \right)^2 \quad (\text{C.26})$$

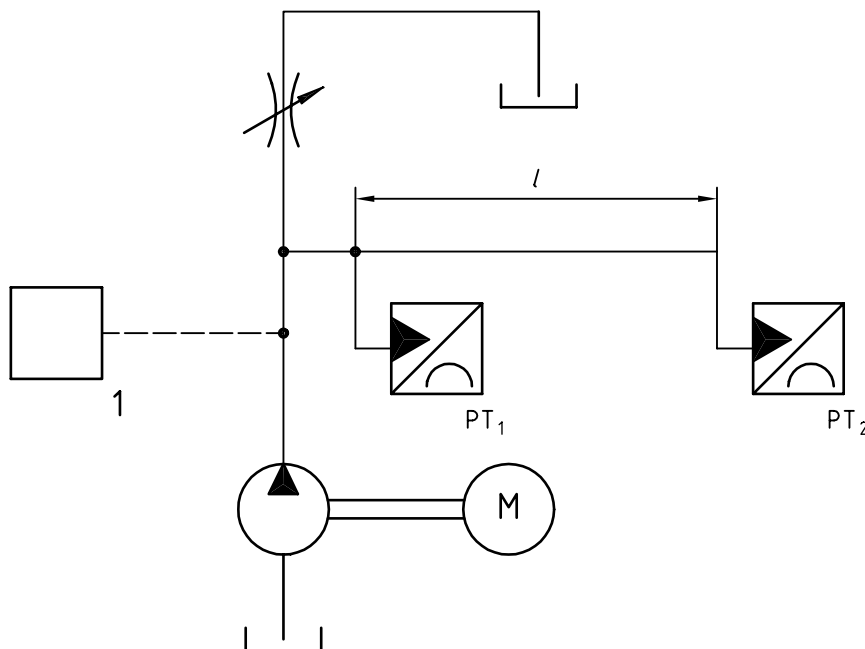
Thus, equation (C.10) becomes;

$$c_N = c_O - \frac{\sum_1^N \left[\varepsilon_x \frac{\partial \varepsilon_x}{\partial c} + \varepsilon_y \frac{\partial \varepsilon_y}{\partial c} \right]}{\sum_1^N \left[\left(\frac{\partial \varepsilon_x}{\partial c} \right)^2 + \left(\frac{\partial \varepsilon_y}{\partial c} \right)^2 \right]} \tag{C.27}$$

A MATLAB® program to perform this iteration is given in annex D.

C.3 The "antiresonance" of a closed-end pipe method

This method is based on the measurement of frequency resonances of a rigid pipe, closed at one end. This pipe is introduced into the hydraulic circuit at point X. A pressure transducer is located at each end of the closed-end pipe.



Key
 1 Secondary source

Figure C.1 — Position of transducers

To be valid, this method requires that the pressure ripples of the circuit cover at least the frequency range between the first and the third "antiresonance" frequencies of the closed-end pipe.

At the closed end of the pipe, where pressure transducer PT₂ is located, we get Q_{2 → 1} = 0

From equation (C.1):

$$Q_{2 \rightarrow 1} = AP_2 + BP_1 = 0$$

$$\frac{P_2}{P_1} = -\frac{B}{A} = \frac{-1}{\cos \left[\frac{l}{c}(a - jb) \right]} \tag{C.28}$$

The modulus of transfer function $\frac{P_2}{P_1}$ is a maximum at each "antiresonance" frequency. The modulus is:

$$\left| \frac{P_2}{P_1} \right| = \frac{1}{\sqrt{\cos^2 \frac{la}{c} + \sinh^2 \frac{lb}{c}}} \quad (\text{C.29})$$

The frequencies where maxima occur are $f_1, f_2, f_3 \dots$

At these particular frequencies, the modulus derivative is equal to zero for the value of c expressed in equation (C.12).

$$\frac{b}{a} \sinh \frac{2lb}{c_0} - \sin \frac{2la}{c_0} = \varepsilon \quad (\text{C.30})$$

Thus:

c_0 = old value of c ;

c_N = new value of c ;

ε = error due to inaccuracy of c .

$$\frac{b}{a} \sinh \frac{2lb}{c_0} - \sin \frac{2la}{c_0} = \varepsilon \quad (\text{C.31})$$

$$\frac{b}{a} \sinh \frac{2lb}{c_N} - \sin \frac{2la}{c_N} = 0 \quad (\text{C.32})$$

The difference between equations (C.31) and (C.32) is obtained approximately.

Knowing that: $\frac{1}{c_0} - \frac{1}{c_N} \approx 0$

$$\text{then } \frac{2lb^2}{a} \left(\frac{1}{c_0} - \frac{1}{c_N} \right) \cosh \left(\frac{2lb}{c_0} \right) - 2la \left(\frac{1}{c_0} - \frac{1}{c_N} \right) \cos \left(\frac{2la}{c_0} \right) \approx \varepsilon \quad (\text{C.33})$$

Expressing that $c_N = c_0 + \Delta c$, we get:

$$\Delta c = \frac{c_0^2 b \sinh \frac{2lb}{c_0} + a \sin \frac{2la}{c_0}}{2l \left[b^2 \cosh \frac{2lb}{c_0} + a^2 \cos \frac{2la}{c_0} \right]} \quad (\text{C.34})$$

The iterative calculation is performed as follows:

a) Define the first iterative value of c from the equation

$$c_0 = \frac{4f_k l}{(2k-1)} \quad (\text{C.35})$$

where

f_k is the frequency of the k th maximum of the transfer function $|H_{21}|$

l is the length of pipe

- b) Using equation (C.34), calculate Δc , and then c_N .
- c) Repeat the last step until $\Delta c \approx 0$

The value of c which is finally found is a particular value of the speed of sound that satisfies equation (C.15).

A MATLAB® program to perform the iteration is given in annex E.

C.4 Validity of calculation of c

This value of c is the effective speed of sound only if $f_2/f_1 \approx 3$. If the measurements of the spectrum are good, we note that $f_k/(2k - 1)$ is approximately constant.

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Annex D (informative)

Example of speed of sound calculation in MATLAB® language using three pressure transducers in a pipe (Method 1)

```

function c=speedsnd(l12,l23,d,visc,c0,omega,h12,h32,coher,g)
% function c=speedsnd(l12,l23,d,visc,c0,omega,h12,h32,coher,g)
%   Determination of the velocity of the wave propagation
%   pulsations (speed of sound) in a fluid enclosed by a homogeneous
%   and straight pipe using the THREE PRESSURE TRANSDUCER - METHOD 1
%   transducer 2 between 1 & 3
%   c    final value of the speed of sound          m.s-1
%   l12  distance between pressure transducers 1 & 2    m
%   l23  distance between pressure transducers 2 & 3    m
%   d    inside diameter of the rigid pipe             m
%   visc kinematic viscosity of the fluid at test conditions  m2.s-1
%   c0   initial chosen value of the speed of sound     m/s
%   omega (2.pi.f) vector of individual frequencies
%         used in the measurements
%   h12, h32 two-dimensional matrices containing
%            respectively, the transfer functions P1/P2
%            and associated coherence; and P3/P4 and
%            associated coherence. That is h12(:,1) and
%            h32(:, 1) contain the transfer function in complex number format and h12(:, 2) and
%            h32(:, 2) contain corresponding real
%            number coherences. These matrices are of
%            the same length as omega vector
%   coher minimum value for coherence for
%         measurements to be valid for calculation
%         (normally coher = 0.95)

```

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```
% g printing option (text & graphics on screen if g==1)
%----- LOOKING FOR AVAILABLE FREQUENCIES ( coherence > min value )
nrc=0; %initialisation of the number of available frequencies
    for nc=1:length(omega),
        if ( h12(nc,2).*h32(nc,2)>=coher*coher ),
            nrc=nrc+1;
            nv(nc)=1; % indexation of the available frequencies
        else
            nv(nc)=0; % indexation of the unavailable frequencies
        end %if
    end %for
    nv(1)=0; % null frequencies not taken into account
%----- BEGINNING OF THE LOOP ALGORITHM -----
a= omega(:) + sqrt(2*omega(:)*visc)/d;
b= 4*visc/(d*d) + sqrt(2*omega(:)*visc)/d;
amjb=a(:)-j*b(:);
l12xamjb=l12*amjb;
l23xamjb=l23*amjb;

ik=1; % init number of iterations of the algorithm
c=c0;
dc=10;

while ( abs(dc/c) > 0.0001),
    memc(ik)=c; % memorise number of successive values
                % for optional observations

    l12_=l12xamjb /c;
    l23_=l23xamjb /c;

    E = nv(:).*( sin(l23_).*h12(:,1) +sin(l12_).*h32(:,1) - sin(l12_+l23_) );
```

```

dEsurdc = nv(:).*amjb(:)/(c*c) .* ( - l23*cos(l23_).*h12(:,1) -
l12*cos(l12_).*h32(:,1) +(l12+l23)*cos(l12_+l23_ ) );

dc= - sum(E.*conj(dEsurdc) ) / sum(dEsurdc.*conj(dEsurdc) );

dc=real(dc);          % real: force c to be a real value

c=abs(c+dc);         % abs: force c to be a positive value

%----- TEXTS ON SCREEN ( optional ) -----

if (g==1),
    if(ik==1)
        fprintf('\n determination of speed of sound with coherence imposed >
%g\n',coher);
        fprintf(' number of available frequencies: %g on %g
maxi\n',nrc,length(omega));
        fprintf(' c%g= %6.2f dc= %6.4f\n',ik,c0,dc );
    else
        fprintf(' c%g= %6.2f dc= %6.4f\n',ik,memc(ik),dc );
    end
else;
end; %if(g==1)

%-----

%----- WARNING MESSAGE -----

if(ik>50)
    fprintf(' number of iteration values > 50\n');
    fprintf(' something is wrong ! , verify the initial values \n');
    return
else;
end; %if(ik>50)

ik=ik+1; %increment the number of iterations

```

```
end % end of loop while( abs(dc/c) > 0.0001 )

%----- GRAPHICS (optional)-----

if (g==1),
    fprintf('\n final value of speed of sound = %6.0f m/s \n\n',real(c) );
    np=1:ik-1;
    plot(np,memc(np),'*w',np,memc(np) );
    grid;xlabel(' * ---> NUMBER OF ITERATIONS');
    ylabel('speed of sound m/s');
    title('progression of the algorithm ');
    text(0.5,0.5,['final value=',num2str(c)],'sc');
else;
end %if g==1

% ----- END FUNCTION speedsnd.m -----
```

Annex E (informative)

Example of speed of sound calculation in MATLAB® language using two pressure transducers in a closed-end pipe (Method 2)

```

function cele=lsur4 (f1,f2,k1,k2,visc)
%function cele=lsur4 (f1,f2,k1,k2,visc)
%    f1 first antiresonant frequency
%    f2 second antiresonant frequency
%    k1 number of the maxima that occur at f1
%    k2 number of the maxima that occur at f2
%
l=1;    d=10e-3;
w1=2*pi*f1;
aa=w1+sqrt(2*w1*visc/d^2);
bb=4*visc/d^2+sqrt(2*w1*visc/ d^2);
e=1e-5;
dc=10;
c=4*l*f1/(2*k1-1);
while(abs(dc)>e)
    a=aa*l/c;
    b=bb*l/c;
    dc=c/2 *( b.*sinh(2*b) + a.*sin(2*a) ) ./ ( b.^2.*cosh(2*b) + a.^2.*cos(2*a) );
    c=abs(c+dc);
    fprintf('dc= %e  c= %e \n',dc,c);
    if dc>2000
        return;
    end
end
c1=c;

```

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```
w2=2*pi*f2;
aa=w2+sqrt(2*w2*visc/ d^2);
bb=4*visc/d^2+sqrt(2*w2*visc/d^2);
e=1e-5;
dc=10;
c=4*I*f2/(2*k2-1);
while(abs(dc)>e)
    a=aa*I/c;
    b=bb*I/c;
    dc=c/2 *( b.*sinh(2*b) + a.*sin(2*a) ) ./ ( b.^2.*cosh(2*b) + a.^2.*cos(2*a) );
    c=abs(c+dc);
    fprintf('dc= %e c= %e \n',dc,c);
    if dc>2000
        return;
    end
end
c2=c;
% Test to validate the measurement
if abs( (c1-c2) / (c1+c2) ) < 0.05
    c=(c1+c2)/2;
    ecart=abs(c1-c2)/2;
    fprintf('cele moy = %e ecart =+- %e \n',c,ecart);
end
```


Bibliography

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