International Standard

ISO 15086-2

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

Part 2:
Measurement of the 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

Second edition
2025-02

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Contents

Foreword

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

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This document was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 8, *Product testing*.

This second edition cancels and replaces the first edition (ISO 15086-2:2000), which has been technically revised.

The main changes are as follows:

— the frequency range of pressure ripples has been revised;

— the symbol units, the symbol B_e, subscript O and N have been added to Table 1;

— the symbol f_0 (first acoustic antiresonance frequency) has been replaced by f_{a1};

— Figures 3 and C.1 have been added;

— Figures 1, 2 and 4 have been corrected;

— Formulae 1, C.2, and C.3 have been corrected;

— Annex D has been revised;

— various additional editorial modifications have been made.

A list of all parts in the ISO 15086 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 ripple 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 document, is based upon the application of plane wave transmission line theory to the analysis of pressure ripple in rigid pipes[1].

Two different measurement approaches are presented, namely the use of

— three pressure transducers in a pipe, and

— 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. This method can be performed simultaneously with the hydro-acoustical measurement methods specified in ISO 10767-1, ISO 10767-3 and ISO 15086-3, using the same equipment and measurements.

Either method is suitable 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 the 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 document 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 document is applicable to all types of hydraulic circuit operating under steady state conditions, irrespective of size, for pressure pulsations over a frequency range from 10 Hz to 3 kHz.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 5598, *Fluid power systems and components — Vocabulary*

ISO 80000-1, *Quantities and units — Part 1: General*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

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* (3.1) source within the system

3.3
fundamental frequency
lowest frequency of *pressure ripple* (3.2) measured by the frequency-analysis instrument

3.4
harmonic
sinusoidal component of the *pressure ripple* (3.2) or *flow ripple* (3.1) occurring at an integer multiple of the *fundamental frequency* (3.3)

Note 1 to entry: 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* (3.1) and consequently *pressure ripple* (3.2) in the circuit

3.6
measurement pipe
pipe in which the pressure transducers are mounted

3.7
impedance
complex ratio of the *pressure ripple* (3.2) to the *flow ripple* (3.1) occurring at a given point in a hydraulic system and at a given frequency

3.8
acoustic antiresonance frequency
frequency at which the magnitude of the entry *impedance* (3.7) of the *measurement pipe* (3.6) is at a minimum.

4   Symbols

Table 1 — Symbols

Symbol	Description	Unit
A, A', B, B'	Complex coefficients	$\mathrm{m^3 \cdot s^{-1} \cdot Pa^{-1}}$
a, b	Frequency-dependent wave propagation coefficients	$\mathrm{rad \cdot s^{-1}}$
B_e	Effective bulk modulus of elasticity	Pa
c	Speed of sound in the fluid	$\mathrm{m \cdot s^{-1}}$
d	Internal diameter of measurement pipe	m
f	Frequency of the wave pulsation harmonic	Hz
f_i	i^{th} harmonic frequency	Hz
f_{ai}	i^{th} acoustic antiresonance frequency	Hz
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	Complex operator ($\sqrt{-1}$)	—
L	Distance between transducers 1 and 2 (Method 1)	m
L'	Distance between transducers 2 and 3 (Method 1)	m
l	Distance from $\mathrm{PT_1}$ to the end of the tube (Method 2)	m
P_1	Pressure ripple of transducer $\mathrm{PT_1}$ (complex number)	Pa
P_2	Pressure ripple of transducer $\mathrm{PT_2}$ (complex number)	Pa
P_3	Pressure ripple of transducer $\mathrm{PT_3}$ (complex number)	Pa
$Q_{1 \to 2}$	Flow ripple at location 1, from 1 to 2 (complex number)	$\mathrm{m^3 \cdot s^{-1}}$
$Q_{2 \to 1}$	Flow ripple at location 2, from 2 to 1 (complex number)	$\mathrm{m^3 \cdot s^{-1}}$

Table 1 *(continued)*

Symbol	Description	Unit
$Q_{2\to3}$	Flow ripple at location 2, from 2 to 3 (complex number)	$m^3 \cdot s^{-1}$
S_i	Coherence function corresponding to measurement frequencies, f_i	—
ε	Error (complex number)	—
$\overline{\varepsilon}$	Conjugate of complex number ε (complex number)	—
ε_x	Real part of ε	—
ε_y	Imaginary part of ε	—
ρ	Density of fluid	$kg \cdot m^{-3}$
v	Kinematic viscosity of fluid	$m^2 \cdot s^{-1}$
ω	Angular frequency ($2\pi f$)	$rad \cdot s^{-1}$
Subscript O	Index for old value	—
Subscript N	Index for new value	—
NOTE $H, H', H^*, P_1, P_2, P_3, Q_{1\to2}, Q_{2\to1}, Q_{2\to3}$ are all frequency-dependent terms and hence are designated by upper-case letters.		

Units used in this document shall be in accordance with ISO 80000-1.

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

5 Instrumentation

5.1 Static measurements

The instruments used to measure

a) mean flow (Method 1 only),

b) mean fluid pressure, and

c) fluid temperature

shall at least meet the requirements for "industrial class" accuracy of measurement, i.e. class C as given in [Annex A](#).

5.2 Dynamic measurements

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

a) resonant frequency: ≥30 kHz,

b) linearity: ±1 %,

c) preferably include acceleration compensation, and

shall at least meet the requirements for "industrial class" accuracy of measurement, i.e. class C as given in [Annex B](#).

The instruments need not respond to steady-state pressure. It can 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: ±0,5 %,

b) phase within: ±0,5°, and

c) frequency within: ±0,5 %

over the frequency range from 10 Hz to 3 kHz.

NOTE   Conformity with the above specification results 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 used).

Suitable alternatives include

— an auxiliary valve with a rotating spool allowing flow to pass to the return line over part of its rotation, and

— a high response electrohydraulic valve driven by a frequency generator. The high response electrohydraulic valve may be operated with a white noise signal to obtain significant pressure ripple measurements at each frequency of interest.

6.2   Generator vibration

If necessary, the measurement pipe shall be structurally isolated from the generator to minimize vibration, e.g. when some obvious pipe vibrations are occurring based on on-site experience.

7   Test conditions

7.1   General

The required operating conditions shall be maintained throughout each test within the limits specified in Table 2.

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 3.

7.4   Mean fluid pressure

The mean fluid pressure 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 2 — Permissible variations in tests conditions

Test parameter	Permissible variation
Mean flow	±2 %
Mean pressure	±2 %
Temperature	±2 °C

Table 3 — Required accuracy of fluid property data

Property	Required accuracy
Density	±2 %
Viscosity	±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 ±0,5 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 used.

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 speed 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.

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 shall be used 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 4.

Table 4 — 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.
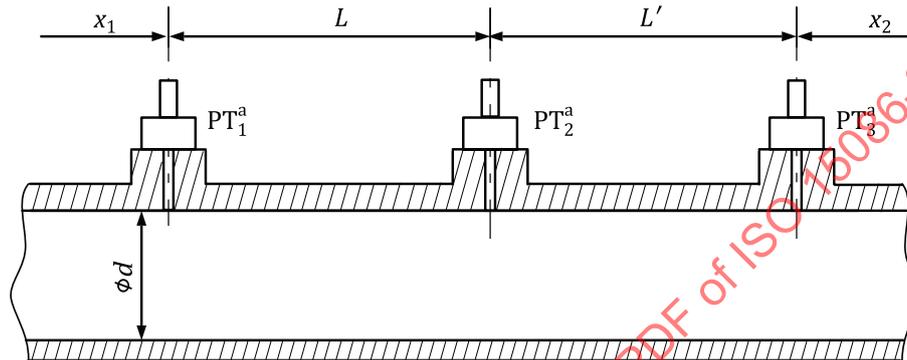
^a Pressure transducer.

NOTE x_1 and x_2 are the distances between each end of the measurement pipe and the nearest pressure transducer.

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.

The measurement pipe shall take 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 has a temperature that is as uniform as possible along its length and does not contain gas bubbles.

To achieve these objectives, the measurement pipe shall be terminated by a bleed valve. Prior to measurements being taken, the bleed valve shall be opened for a period 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 shall not introduce significant extra volume at the end of the line when the valve is in the closed position. The fitting at the end of the pipe where the bleed valve and transducer PT_2 are connected shall be of the same internal diameter as the measurement pipe. The bleed valve shall be a valve without free-moving internal parts, such as a needle valve.

The pressure transducers, PT_1 and PT_2 in Figure 2 a), shall be located at each end of the measurement pipe. PT_2 shall be mounted within $3d$ of the end of the pipe, where d is the internal diameter of the pipe. PT_1 shall

be mounted within 5*d* of the point where the measurement pipe is connected to the main circuit, where *d* is the internal diameter of the pipe.

The internal diameter of the fitting between PT_1 and the measurement pipe shall be the same as the internal diameter of the measurement pipe. 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 bleed valve assembly.

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

To maximize the pressure ripple levels, the distance between the pump (or the noise generator if in use) and the loading valve should not be greater than one-fifth of the measurement pipe length where possible.

The safety relief valve should be set to a cracking pressure at least 10 % higher than the mean test pressure.

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*, from PT_1 to the end of the tube shall be defined according to the first acoustic antiresonance frequency f_{a1} by Formula (1).

$$l = \frac{1}{4 f_{a1}} \sqrt{\frac{B_e}{\rho}}$$
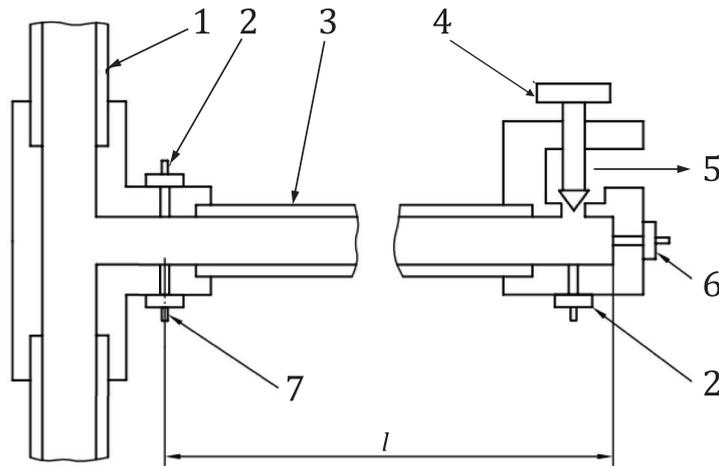(1)

The effective bulk modulus B_e may 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_{a1} shall be chosen in the range 100 Hz to 200 Hz.

The distance from PT_1 to the end of the tube shall be measured to an accuracy of ±0,5 mm.
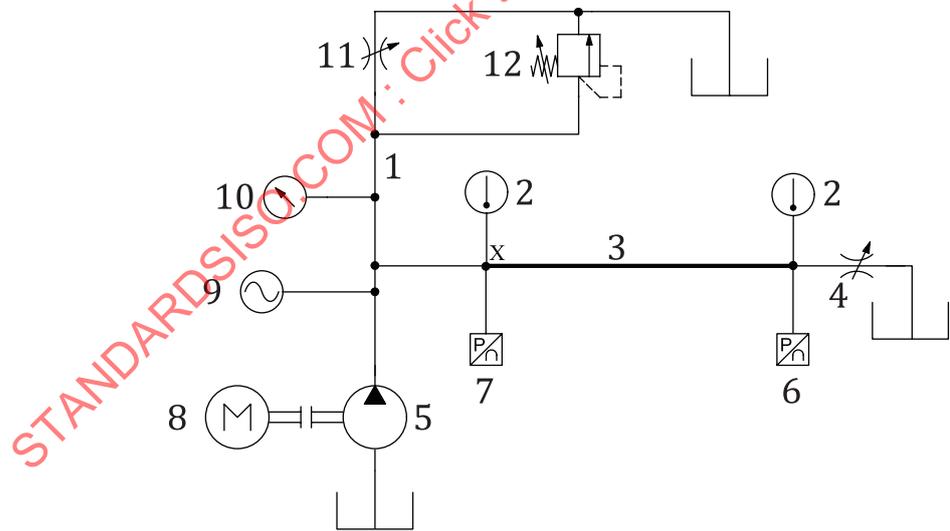
a) Circuit layout

b) Example of transducer locations and bleed valve mounting

Key

1   through-flow pipe
2   temperature transducer
3   measurement pipe
4   bleed valve
5   pump
6   pressure transducers PT_2
7   pressure transducers PT_1
8   electric motor
9   hydraulic noise generator
10 pressure gauge
11 loading valve
12 safety valve

Figure 2 — Typical antiresonance test arrangement

8.5   Calibration of pressure transducers

Calibration of pressure transducers and signal conditioning is necessary for method 1 only. 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, as shown in Figure 3.
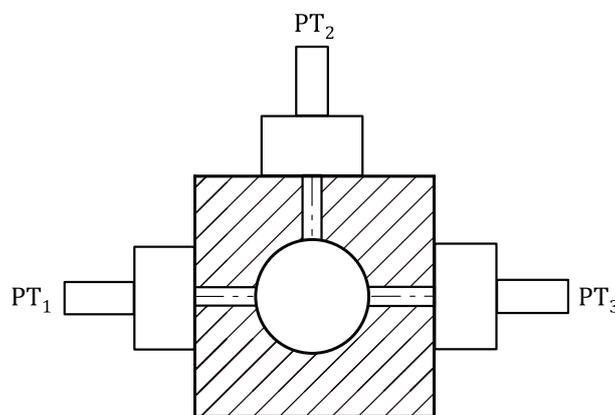

Figure 3 — Example of pressure transducer calibration distribution

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.

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

$$H'_{12} = \frac{P_1}{P_2} \tag{2}$$

$$H'_{32} = \frac{P_3}{P_2} \tag{3}$$

and calculate the coherence function S_i at each frequency f_{ai} over the frequency range. Record the transfer functions obtained during calibration where the associated coherence function S_i is greater than 0,95.

9 Test procedure for Method 1

9.1 Prior to the commencement of tests, operate the hydraulic system for a sufficient period to purge air from the system and to stabilize all variables, including fluid condition, to within the limits given in Table 2. 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.

$$H^*_{12} = \frac{P_1}{P_2} \tag{4}$$

$$H^*_{32} = \frac{P_3}{P_2} \tag{5}$$

and calculate the coherence function S_i at each frequency f_{ai} 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 4.

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 Formulae (2) and (3).

$$H_{12} = \frac{H^*_{12}}{H'_{12}} \tag{6}$$

$$H_{32} = \frac{H^*_{32}}{H'_{32}} \tag{7}$$

If H'_{12} and H'_{32} have not been recorded at the frequencies of H^*_{12} and H^*_{32}, interpolation shall be used between the nearest frequencies where values are available.

If correction is not necessary (see 8.5), then $H_{12} = H^*_{12}$ and $H_{32} = H^*_{32}$.
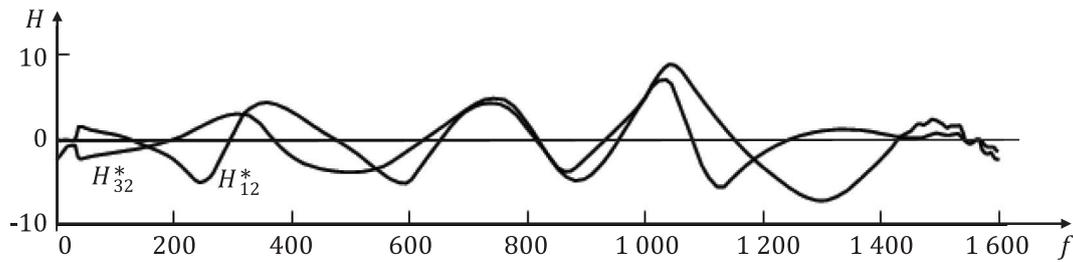
a) Modulus of transfer functions H_{12}^* and H_{32}^*
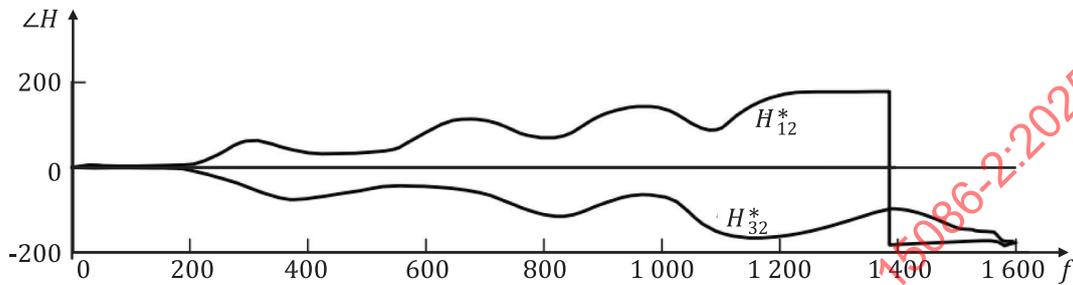
b) Phase of transfer functions H_{12}^* and H_{32}^*

Key

H $|H|/(\text{dB})$

f $f/(\text{Hz})$

$\angle H$ $\angle H/(°)$

f $f/(\text{Hz})$

Figure 4 — Typical example of transfer functions H_{12}^* and H_{32}^*

9.4 The procedure given in Annex C may be used to calculate the speed of sound using data at each frequency where the associated coherence function S_i is greater than 0,95. The least-squares error procedure given in C.2 allows the speed of sound, averaged over the frequency range investigated, to be calculated.

9.5 Calculate the mean fluid speed by dividing the mean flow by the internal cross-sectional area of the measurement pipe. If the mean fluid speed 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 to purge air from the system and to stabilize all variables, including fluid condition, to within the limits given in Table 2. Particular attention should be given to obtaining a representative fluid characteristic, especially the bulk modulus.

The bleed valve shall be fully open to allow flow through the measurement pipe during this stabilization period. The restrictor valve downstream of the bleed valve shall 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 shall be closed and, if necessary, the mean pressure re-established through adjustment of the loading valve.

10.2 Take the ensemble average of at least 16 time-series pressure transfer functions and calculate the coherence function S_i at each frequency f_i over the frequency range. Disregard points for which the coherence function is less than 0,95.

$$H_{21}^{*} = \frac{P_2}{P_1} \qquad (8)$$

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 Formula (9).

$$H_{21} = \frac{H_{21}^{*}}{H_{21}'} \qquad (9)$$

10.4 Identify and record the frequencies for which the transfer function H_{21} is a maximum. The procedure given in C.3 may be used to calculate the speed of sound.

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) a reference to this document, i.e. ISO 15086-2:2025;

c) name of persons performing the test;

d) reference specifications of fluid tested;

e) date and place of tests;

f) 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;

3) fluid density;

4) fluid temperature;

5) mean pressure;

6) mean flow in rigid pipe for Method 1.

11.3 Test results

The test report shall contain the following test results.

a) the speed of sound;

b) temperature at the entry to the measurement pipe and mean pressure 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 document:

"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. Note 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

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

Class of measurement	A	B	C
Instantaneous pressure %	±1,5	±3,0	±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
(informative)

Data reduction algorithms

C.1   General

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.

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, as shown in Figure C.1.
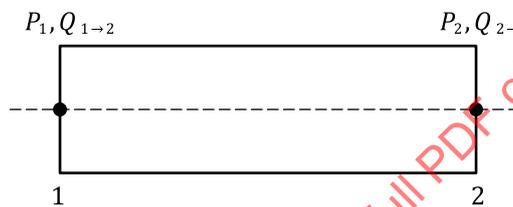

Figure C.1 — Example of pipe

$$Q_{1\rightarrow2} = AP_1 + BP_2$$
$$Q_{2\rightarrow1} = AP_2 + BP_1 \tag{C.1}$$

$$A = \frac{-\pi d^2 \mathrm{j}\omega}{4\rho c(a-\mathrm{j}b)} \cot\left[(a-\mathrm{j}b)\frac{L}{c}\right] \tag{C.2}$$

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

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

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

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.

Applying Formula (C.1) to a rigid pipe equipped with three pressure transducers PT_1, PT_2 and PT_3, set at distances L and L' respectively, yields:

$$Q_{2 \to 1} = AP_2 + BP_1 \tag{C.6}$$

$$Q_{2 \to 3} = A'P_2 + B'P_3 \tag{C.7}$$

At pressure transducer PT_2, we get:

$$Q_{2 \to 1} + Q_{2 \to 3} = 0 \tag{C.8}$$

$$(A + A')P_2 + BP_1 + B'P_3 = 0 \tag{C.9}$$

Then:

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

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

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

$$1 + \frac{B}{A+A'}(H_{12}) + \frac{B'}{A+A'}(H_{32}) = \varepsilon \tag{C.11}$$

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

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

C.2.2   Procedure for numerical calculation of the speed of sound

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

$$E = \sum_1^N \varepsilon \bar{\varepsilon} \tag{C.13}$$

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

$\sum_1^N$ represents the sum of the variables corresponding to the frequencies of the 1st to the Nth harmonics.

The total error, E, shall be evaluated for a set of speed of sound values from $0{,}9c_0$ to $1{,}1c_0$ in increments of $0{,}5$ m·s^{-1} or less, where $c_0 = \sqrt{B_e / \rho}$. The measured speed of sound is where the error, E, is at a minimum. If the minimum value of error E is found to be at the start or end of the range of speed of sound values, then the range shall be extended by an additional $0{,}1c_0$ at the start or end, and the error recalculated until the error, E, exhibits a clear minimum within the range. If a clear minimum cannot be identified, or if there are multiple local minima within this range, then the test results are invalid.

A MATLAB®[1]) program to perform this iteration is given in Annex D.

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1)   This tool is not the only one on the market.

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 as shown in Figure 2.

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 PT_2 is located, we get $Q_{2\rightarrow1} = 0$.

From Formula (C.1), we get:

$$Q_{2\rightarrow1} = AP_2 + BP_1 = 0 \tag{C.14}$$

$$\frac{P_2}{P_1} = -\frac{B}{A} = \frac{-1}{\cos\left[\dfrac{l}{c}(a-\mathrm{j}b)\right]} \tag{C.15}$$

The modulus of transfer function P_2/P_1 is a maximum at each "antiresonance" frequency. The modulus is:

$$\left|\frac{P_2}{P_1}\right| = \frac{1}{\sqrt{\cos^2\dfrac{la}{c}+\sinh^2\dfrac{lb}{c}}} \tag{C.16}$$

The frequencies where maxima occur are $f_{a1}, f_{a2}, f_{a3} \dots$

At these particular frequencies, the modulus derivative is equal to zero. By differentiating Formula (C.16), it can be obtained:

$$\frac{b}{a}\sinh\frac{2lb}{c_O} - \sin\frac{2la}{c_O} = 0 \tag{C.17}$$

$$\frac{b}{a}\sinh\frac{2lb}{c_O} - \sin\frac{2la}{c_O} = \varepsilon \tag{C.18}$$

$$\frac{b}{a}\sinh\frac{2lb}{c_N} - \sin\frac{2la}{c_N} = 0 \tag{C.19}$$

c_O is the old value of c;

c_N is the new value of c;

ε is the error due to inaccuracy of c.

The difference between Formulae (C.18) and (C.19) is obtained approximately.

Knowing that:

$$\frac{1}{c_O} - \frac{1}{c_N} \approx 0 \tag{C.20}$$

Then:

$$\frac{2lb^2}{a}\left(\frac{1}{c_O}-\frac{1}{c_N}\right)\cosh\left(\frac{2lb}{c_O}\right) - 2la\left(\frac{1}{c_O}-\frac{1}{c_N}\right)\cos\left(\frac{2la}{c_O}\right) \approx \varepsilon \tag{C.21}$$

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

$$\Delta c = \frac{c_0{}^2 \left(b \sinh \dfrac{2lb}{c_0} - a \sin \dfrac{2la}{c_0} \right)}{2l \left(b^2 \cosh \dfrac{2lb}{c_0} - a^2 \cos \dfrac{2la}{c_0} \right)} \tag{C.22}$$

The iterative calculation is performed as follows:

a) Define the first iterative value of c from the Formula (C.23):

$$c_0 = \frac{4 f_{ak} l}{(2k-1)} \tag{C.23}$$

where, f_{ak} is the frequency of the kth maximum of the transfer function $|H_{21}|$.

b) Using Formula (C.22), calculate Δc, and then c_N

c) Repeat until $\left| \dfrac{c_N - c_0}{c_N} \right| < 0{,}000\,1$

The value of c which is finally found is a particular value of the speed of sound.

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 $2{,}9 < (f_{a2}/f_{a1}) < 3{,}1$.

If the measurements of the spectrum are good, we note that $f_{ak}/(2k-1)$ is approximately constant.

Annex D
(informative)

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

```
function c=speedsnd_v2(l12, l23, d, visc, cvec, omega, h12, h32, coher, g)
% function c=speedsnd_v2(l12, l23, d, visc, cvec, omega, h12, h32, coher, g)
% Determination of the velocity of the wave propagation (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
%
% Output values :
%         c :           final value of the speed of sound [m.s-1]
%
%
% Input values :
%
%         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]
%         cvec :        speed of sound vector on which c is evaluated [m/s]
%         omega (2.pi.f) :   vector of individual frequencies used in measurements
%         h12, h32 :    two-dimensional matrices containing respectively, the
%                       transfer functions P1/P2 and associated coherence;
%                       and P3/P4 and associated coherence.
%                       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)
%         g :           printing option for error plot (text & graphics on screen if g==1)
```