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

Part 3: Measurement of hydraulic impedance

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

Partie 3: Mesurage de l'impédance hydraulique

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 documents 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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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 15086-3:2008), which has been technically revised.

The main changes are as follows:

— the symbols P_y, y, $Q_{3\to x}$ and $Q_{3\to 0}$ have been added to Table 1;

— Formula (7) has been added;

— Formulae (3), (8), (13), (14), (16) and (17) have been corrected;

— Figures 1, 2, 3, 5, 6, 7 and 8 have been corrected;

— 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 a closed circuit. During the process of converting mechanical power into fluid power, fluid-borne noise (flow ripple and pressure ripple) is generated. This in turn leads to structure-borne noise and airborne noise. The transmission of fluid-borne noise is influenced by the impedance of the components installed in the hydraulic circuit.

This document adopts the concepts of ISO 15086-1 which describe the basis for the methods of measurement that make it possible to determine the characteristics of fluid-borne noise emitted or transmitted by hydraulic transmission systems.

Clause 6 of this document describes the method for measuring the hydraulic impedance of a single-port component (local hydraulic impedance) and Clause 7 describes the method for measuring the hydraulic impedance matrix of a two-port hydraulic component.

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

Part 3: Measurement of hydraulic impedance

1 Scope

This document describes the procedure for determining the impedance characteristics of hydraulic components by means of measurements from pressure transducers mounted in a pipe.

This document is applicable to passive components, irrespective of size, operating under steady-state conditions, 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 80000-1, *Quantities and units — Part 1: General*

ISO 1219-1, *Fluid power systems and components — Graphical symbols and circuit diagrams — Part 1: Graphical symbols for conventional use and data-processing applications*

ISO 5598, *Fluid power systems and components — Vocabulary*

ISO 15086-1:2001, *Hydraulic fluid power — Determination of the fluid-borne noise characteristics of components and systems — Part 1: Introduction*

ISO 15086-2:2000, *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*

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
fluctuation of flow rate in the hydraulic fluid

3.2
pressure ripple
fluctuating component of pressure in the hydraulic fluid, caused by interaction of the source *flow ripple* (3.1) with the system

3.3
pulse generator
hydraulic component generating a periodic *flow ripple* (3.1) and consequently *pressure ripple* (3.2) in a circuit, or a hydraulic component generating a pressure ripple and, consequently, a flow ripple in a circuit

3.4
fundamental frequency
lowest frequency of the *pressure ripple* (3.2) [or *flow ripple* (3.1)] considered in a theoretical analysis or measured by an instrument

EXAMPLE A hydraulic pump or motor with a shaft frequency of N revolutions per second can be taken to have a fundamental frequency of N Hz. Alternatively, for a pump or motor with k displacement elements, the fundamental frequency can be taken to be Nk Hz, provided that the measured behaviour does not deviate significantly from cycle to cycle.

3.5
harmonic
sinusoidal component of a signal that occurs at an integer multiple of the *fundamental frequency* (3.4)

Note 1 to entry: A harmonic can be represented by its amplitude and phase, or by its real and imaginary parts.

3.6
impedance
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

3.7
admittance
reciprocal of *impedance* (3.6)

3.8
hydro-acoustic energy
fluctuating part of the energy in a liquid

4 Symbols

Table 1 — Symbols

Symbol	Description	Unit
A_e	complex coefficient (term of admittance matrix between transducer PT3 and component 0)	$m^3 \cdot s^{-1} \cdot Pa^{-1}$
A_x	complex coefficient (term of admittance matrix between transducers PT*x* and PT3)	$m^3 \cdot s^{-1} \cdot Pa^{-1}$
A_{xy}	terms of admittance matrix (for x and y equal to 1 or 2)	$m^3 \cdot s^{-1} \cdot Pa^{-1}$
B_e	complex coefficient (term of admittance matrix between transducer PT3 and component 0)	$m^3 \cdot s^{-1} \cdot Pa^{-1}$
B_x	complex coefficient (term of admittance matrix between transducers PT*x* and PT3)	$m^3 \cdot s^{-1} \cdot Pa^{-1}$
c	speed of sound in the fluid	$m \cdot s^{-1}$
f_{min}	minimum frequency	Hz
f_{max}	maximum frequency	Hz
H_{x3}	transfer function between pressure ripples P_x and P_3	—
L	distance between transducers	m
p_m	mean test pressure	MPa
P_e	Fourier transform of pressure ripple at upstream port of component	Pa

Table 1 *(continued)*

Symbol	Description	Unit
P_s	Fourier transform of pressure ripple at downstream port of component	Pa
P_x	Fourier transform of pressure ripple at location *x*, where *x* is the number of the pressure transducer, equal to 1, 2 or 3, corresponding to PT1, PT2 or PT3, respectively	Pa
P_y	Fourier transform of pressure ripple at location *y*, where *y* is the number of the pressure transducer, equal to 4, 5 or 6, corresponding to PT4, PT5 or PT6, respectively	Pa
P_1, P_2 and P_3	Fourier transform of pressure ripple at the location of pressure transducer 1 (PT1), pressure transducer 2 (PT2) and pressure transducer 3 (PT3), respectively	Pa
q_m	mean flow rate	$l \cdot s^{-1}$
$Q_{e \to 0}$	Fourier transform of flow ripple into upstream port of component (0)	$m^3 \cdot s^{-1}$
$Q_{s \to 0}$	Fourier transform of flow ripple into downstream port of component (0)	$m^3 \cdot s^{-1}$
$Q_{3 \to x}$	Fourier transform of flow ripple at the location of pressure transducer 3 (PT3), defined as positive when towards location of pressure transducer *x*	$m^3 \cdot s^{-1}$
$Q_{3 \to 0}$	Fourier transform of flow ripple at the location of pressure transducer 3 (PT3), defined as positive when towards location of pressure transducer (0)	$m^3 \cdot s^{-1}$
T_m	fluid mean temperature	°C
x	number of the pressure transducer, equal to 1, 2 or 3, corresponding to PT1, PT2 or PT3, respectively	—
y	number of the pressure transducer, equal to 4, 5 or 6, corresponding to PT4, PT5 or PT6, respectively	—
Z_e	hydraulic impedance	$Pa \cdot s \cdot m^{-3}$
$Z_{e \to 0}$	hydraulic impedance of component (0)	$Pa \cdot s \cdot m^{-3}$
ν	kinematic viscosity	$mm^2 \cdot s^{-1}$ (cSt)
θ	phase of harmonic component (pressure or flow ripple, as appropriate)	degree (°)
$d\theta$	phase precision of the Fourier analyser	degree (°)

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

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

5 Test conditions and accuracy of instrumentation

5.1 Test conditions (permissible variations)

5.1.1 General

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

Table 2 — Permissible variations in test conditions

Test parameter	Permissible variation
Mean flow	±2 %
Mean pressure	±2 %

Table 2 *(continued)*

Test parameter	Permissible variation
Temperature	±2 °C

5.1.2 Fluid temperature

The temperature of the fluid shall be measured at the measuring pipe inlet.

5.1.3 Fluid density and viscosity

The density and viscosity of the fluid shall be known to an accuracy within the limits specified in Table 3.

Table 3 — Required accuracy of fluid property data

Property	Required accuracy %
Density	±2
Viscosity	±5

5.1.4 Mean fluid pressure

The mean pressure of the fluid shall be that measured at the measuring pipe inlet.

5.1.5 Mean flow measurement

The mean flow measurement shall be measured downstream of the measuring pipe (e.g. in cases where the mean flow influences the terms of the admittance or impedance matrix).

5.2 Instrumentation precision

5.2.1 Steady-state accuracy class

The accuracy required shall be in accordance with the values given in ISO 15086-1:2001, Annex A.

5.2.2 Dynamic-state accuracy class

The accuracy required shall be in accordance with the values given in ISO 15086-1:2001, Annex B.

6 Measurement of the impedance of a single-port passive component

6.1 Local impedance — Measurement principle

The hydraulic impedance, $Z_{e\to 0}$, of a component with a single-port connection is defined by Formula (1) and shown diagrammatically in Figure 1:

$$Z_{e\to 0} = \frac{P_e}{Q_{e\to 0}} \tag{1}$$

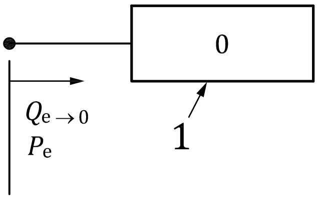
where

P_e is the Fourier transform of the pressure ripple at the component inlet;

$Q_{e\to 0}$ is the Fourier transform of the flow ripple entering the component and regarded as positive when entering the 0 component.

In the high-frequency ranges (> 10 Hz), no convenient systems exist to measure the flow $Q_{e\to0}$.

To enable a flow ripple to be inferred, this test method requires the use of a rigid hydraulic pipe fitted with dynamic pressure transducers having a sufficiently high bandwidth and with the distances between the transducers selected according to the frequency range of interest.



Key

1 component 0

Figure 1 — Key parameters in the measurement of impedance of a single-port component

6.2 Hydraulic impedance

6.2.1 Measurement principle

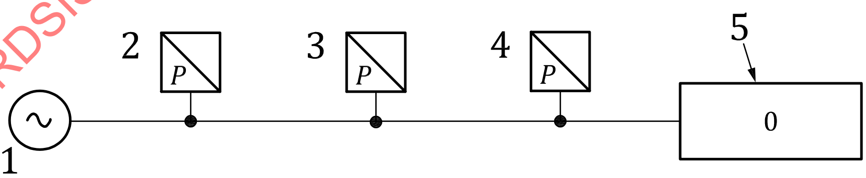
Figure 2 illustrates the principle for measuring the hydraulic impedance, Z_e, at the inlet of the single-port component (0).

NOTE A passive component is not itself a generator of hydro-acoustic energy.

Three dynamic pressure transducers (PT1 to PT3) are connected to the rigid pipe constituting the flow ripple measuring pipe at transducer PT3. The diaphragms of the dynamic pressure sensors should be flush with the inner cylindrical surface of the measuring pipe.

It is assumed that appropriate technical measures have been taken to ensure that the speed of sound in the fluid between PT1 and PT3 is uniform. This requires that the mean temperature of the fluid in the measuring pipe be uniform to within 2 °C along its length and that the internal section of measuring pipes be constant between PT1 and PT3.

The speed of the sound in the measuring pipes is determined by means of the three pressure transducers, PT1 to PT3, in accordance with the algorithm described in ISO 15086-2.



Key

1 pulse generator

2 pressure transducer PT1

3 pressure transducer PT2

4 pressure transducer PT3

5 component 0

NOTE Only the dynamic part of the pressure signal is required for PT1, PT2 and PT3.

Figure 2 — Principle of measuring the impedance of a single-port component

6.2.2 Simplified algorithm for determining the component of the local hydraulic impedance

The flow being determined at the upstream port of component (0) is $Q_{3\to 0}$.

A_x and B_x are the elements of the admittance matrix describing the pipe between PT*x* and PT3 where *x* is 1 or 2 depending on the transducers selected to determine the flows.

A_e and B_e are the elements of the admittance matrix describing the pipe between the inlet of the single-port component (0) and PT3.

By referring to ISO 15086-1, which provides the basic definitions, the algebraic relationships shown in Formulae (2) to (5) are obtained.

$$Q_{3\to 0} = -Q_{3\to x} = -\left(A_x P_3 + B_x P_x\right) \quad (2)$$

$$Q_{e\to 0} = -\frac{A_e Q_{3\to 0}}{B_e} + \frac{\left(A_e^2 - B_e^2\right)}{B_e} P_3 \quad (3)$$

$$P_e = \frac{Q_{3\to 0}}{B_e} - \frac{A_e P_3}{B_e} \quad (4)$$

$$Z_{e\to 0} = \frac{P_e}{Q_{e\to 0}} \quad (5)$$

$$= \frac{Q_{3\to 0} - A_e P_3}{\left(A_e^2 - B_e^2\right) P_3 - A_e Q_{3\to 0}}$$

$$= \frac{-\left(A_x P_3 + B_x P_x\right) - A_e P_3}{\left(A_e^2 - B_e^2\right) P_3 + A_e \left(A_x P_3 + B_x P_x\right)}$$

Formula (6) for the measurement of the component hydraulic impedance, $Z_{e\to 0}$, is derived by dividing the numerator and the denominator of Formula (5) by P_3:

$$Z_{e\to 0} = \frac{-A_x - A_e - B_x \dfrac{P_x}{P_3}}{A_e^2 - B_e^2 + A_e A_x + A_e B_x \dfrac{P_x}{P_3}} \quad (6)$$

where *x* is equal to 1 or 2 according to the frequency ranges being measured.

The transfer function, P_x/P_3, can be directly measured by a suitable frequency-response analyser, but due account shall be taken of the pressure-transducer calibration (see 6.3.3).

6.3 Factors influencing the accuracy of the impedance measurement

6.3.1 General

The various factors influencing the accuracy of the impedance measurement and the precautions to take as a result are described in 6.3.2.

6.3.2 Pulse generator

It is necessary to have a device that is capable of producing a strong pressure ripple with a frequency and an amplitude that remain stable over the required frequency range. Suitable devices are:

a) a piston pump or other pump with a broad-band pressure ripple;

b) a specially designed rotary valve that produces regular flow ripples;

c) an electrodynamic vibrator and actuator;

d) a high-frequency response servovalve;

e) a piezoelectric actuator.

Items c) to e) can be excited using a swept-sinusoid, a periodic broad-band waveform or a random signal.

6.3.3 Pressure transfer function measured by the PT*x*/PT3 pressure transducers and the calibration correction

An accurate measurement of the H_{x3} transfer function requires an initial calibration of the PT*x*/PT3 transducers.

$$H_{x3} = \frac{P_x}{P_3} \tag{7}$$

Calibration shall be undertaken using the technique described in ISO 15086-2:2000, 8.5.

The transducers shall be calibrated under environmental conditions identical to those pertaining for the impedance measurement (e.g. the same mean fluid pressure and same fluid temperature).

Settings of the analyser during calibration shall be identical to those during the impedance measurements (e.g. the same measurement range, window shape, analysis band, signal averaging).

The coherence function obtained when measuring the transfer functions by means of the Fourier analyser is an excellent indication of the validity of the measurements when the signal-to-noise ratio of the transducers is adequate.

The pressure-excitation source level shall be such that the coherence function of the transfer functions measured is greater than 0,95. By averaging a sufficiently large number of spectra, it can be possible to improve the coherence for frequencies where the excitation is low.

The transfer-function measurements taken when measuring the impedances shall be corrected by the use of the calibration transfer functions (see ISO 15086-2:2000, 8.5).

6.3.4 Numerical value of terms *A* and *B* of the pipe section admittance matrix used for the indirect determination of the pulsed flows

6.3.4.1 General

The admittance matrix terms *A* and *B* depend on five factors:

a) transducer spacing;

b) measuring pipe internal diameter;

c) speed of sound in the fluid in the measuring pipe;

d) fluid kinematic viscosity;

e) fluid density.

6.3.4.2 Transducer spacing

6.3.4.2.1 General

The distances between the transducers shall be suitable for the range of analysis frequencies selected and for the upper and lower limits of this analysis band. Generally, one single spacing value is inadequate for carrying out a measurement over a wide frequency range.

At high frequencies, the limitation is due to the fact that the analysis becomes indeterminate when the distance between transducers is equal to half of the wavelength of the pressure ripples.

At very low frequencies, the limitation is due to the fact that the amplitude ratio approaches unity and the phase shift between the transducers approaches zero. The analysis becomes inaccurate when the phase shift between the transducers is less than 10 times the accuracy of the analyser's phase measurement capability.

The distances between the transducers should be measured with an accuracy of ±1 mm.

6.3.4.2.2 Practical rules for establishing the transducer spacing

Firstly, using Formulae (8) and (9), determine the distance, L, for an upper frequency limit, f_{max}, where L_{23} is the distance between the transducers selected to measure the impedance between PT2 and PT3 and L_{12} between PT1 and PT2.

$$\frac{0{,}85c}{2f_{max}} < L_{23} < \frac{0{,}95c}{2f_{max}} \tag{8}$$

$$L_{12} = 1{,}4L_{23} \tag{9}$$

EXAMPLE 1 Substituting f_{max} = 1 600 Hz and c = 1 300 m · s^{-1} into Formula (8) gives:

$$\frac{0{,}85 \cdot 1\,300\ \text{m} \cdot \text{s}^{-1}}{2 \cdot 1\,600\ \text{Hz}} < L_{23} < \frac{0{,}95 \cdot 1\,300\ \text{m} \cdot \text{s}^{-1}}{2 \cdot 1\,600\ \text{Hz}}$$

$$0{,}345\ \text{m} < L_{23} < 0{,}386\ \text{m}$$

With the distance, L, established, the lower limit of the frequency measurement, f_{min}, can be estimated using Formula (10):

$$f_{min} = f_{max} \frac{4d\theta}{180} \tag{10}$$

EXAMPLE 2 If $d\theta$ of the analyser is 0,5°, then Formula (10) gives:

$$f_{min} = 1\,600\ \text{Hz} \cdot \frac{4 \cdot 0{,}5}{180} \approx 18\ \text{Hz}$$

Thus, spacings calculated according to Formulae (8) to (10) allow the correct transfer function measurement in a frequency range between an f_{min} equal to 18 Hz and an f_{max} equal to 1 600 Hz.

The distance between transducer PT3 and the upstream port of component (0) shall be between 0,1 L_{23} and 0,2 L_{23}.

6.3.4.3 Speed of sound in the fluid in the measuring pipe

The speed of sound is used in the determination of the admittance matrix terms describing the measuring pipes.

This parameter depends on the temperature and mean pressure of the fluid flowing in the measuring pipes; these parameters shall, therefore, be set according to the desired test conditions and maintained within the limits specified in Table 2 during the measurements.

6.3.4.4 Density of the fluid circulating in the measuring pipes

The density is used in the determination of the admittance matrix terms describing the measuring pipes.

This parameter depends on the temperature and mean pressure of the fluid flowing in the measuring pipes; these parameters shall, therefore, be set according to the desired test conditions and maintained within the limits specified in Table 2 during the measurements.

6.4 Measurement of local impedance

6.4.1 Test circuit

6.4.1.1 Simplified circuit

A simplified test circuit suitable for measuring the hydraulic impedance of a single-port component is shown in Figure 3.

The test circuit is comprised of the following components:

a) hydraulic pump and electric motor, to ensure that the mean flow and mean pressure of the component being tested are supplied; the pump shall be protected by means of a pressure-relief valve;

b) connecting hose, to connect the pump outlet to the test circuit; if the pump generates a pressure ripple level much greater than the pulse generator, it can be necessary to reduce the pressure ripple level at the pump outlet by means of this hose or another attenuating system; otherwise, the pressure ripple level of the pump can saturate the dynamic pressure transducers PT1 to PT3, or can prevent accurate measurement of the harmonics of the pressure ripple from the pulse generator (see 6.4.1.2);

c) rigid pipes, in which the pressure transducers are mounted as shown in Figure 3, with the distance between the transducers suited to the band of frequencies used;

d) three pressure transducers (PT1 to PT3) arranged on rigid pipes upstream and downstream of the component (preferably miniature flush-membrane-type piezoelectric transducers), used to determine the pressure ripple and flow ripple in the pipes and the speed of sound in the test fluid;

e) pulse generator, capable of generating pulses in the selected frequency band with an adequate level to obtain the correct signal-to-noise ratio (see 6.3.2);

f) adjustable flow-control valve, to allow adjustment of the mean test pressure, p_m, downstream of the test circuit controlled by the pressure gauge;

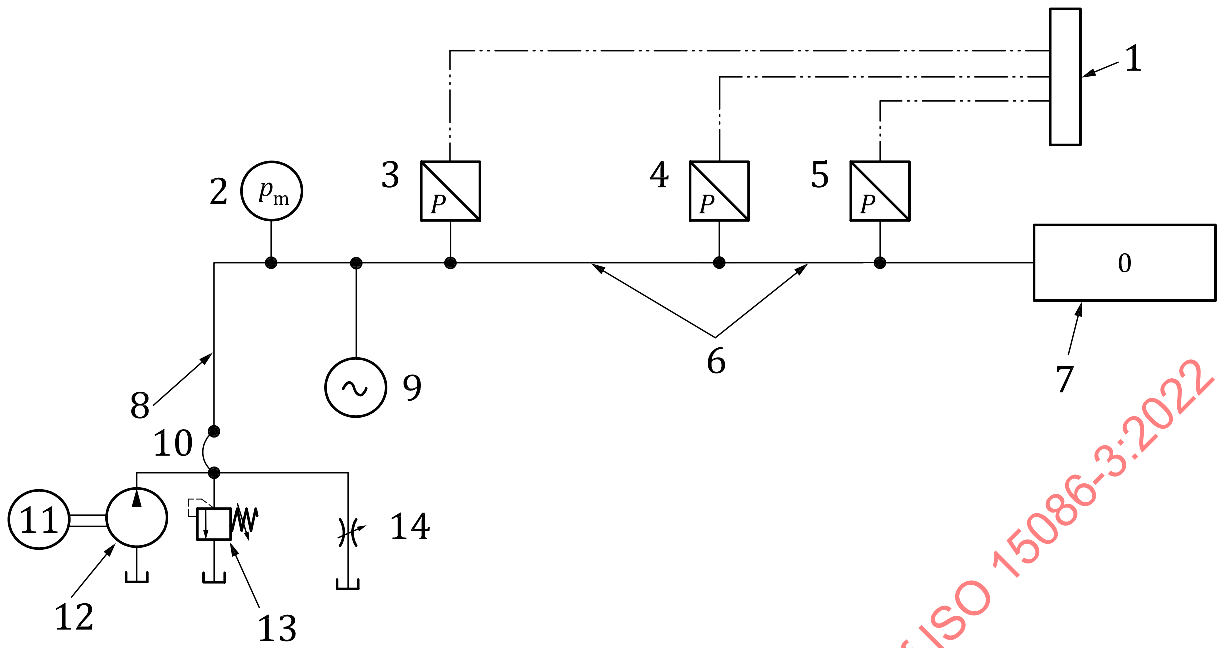
g) cooler (heat exchanger), to ensure temperature regulation of the test fluid controlled by the thermometer;

h) optional mean flowmeter for use in case the mean flow rate in the component under test influences its hydro-acoustic characteristics;

i) component under test;

j) precision transducer or pressure gauge used to monitor the mean pressure during the test.

The test circuit including the single port component shall be carefully purged of air before the measurements are performed.



Key

1	Fourier analyser	8	small-diameter metal pipe
2	mean pressure gauge	9	pulse generator
3	pressure transducer PT1	10	flexible hose
4	pressure transducer PT2	11	electric motor
5	pressure transducer PT3	12	pump
6	metal pipes of the same diameter	13	pressure-relief valve
7	component 0	14	flow-control valve, adjustable

Figure 3 — Simplified test circuit for measuring the impedance of a single port component

6.4.1.2 Isolation of pump pressure ripple

Transmission to the pressure transducers of the pressure ripple produced by the pump should be minimized. This can be achieved by using a flexible hose at least 1 m long, followed by a small-diameter rigid pipe, (typically 0,5 to 0,75 times the diameter of the tube), at least 1 m long.

6.4.2 Test procedure

6.4.2.1 Calibration of the miniature pressure transducers PT1 to PT3

Before taking the measurements, calibrate the pressure transducers (see ISO 15086-2:2000, 8.5) in order to obtain the calibration transfer functions.

6.4.2.2 Adjustment and preliminary operations prior to measuring the impedance

Before carrying out the calibration operation described in 6.4.2.1, steps 6.4.2.2 a) to e) shall be performed.

a) Place the flush-mounted diaphragm pressure transducers in the measuring pipe.

b) Purge the circuit.

c) Adjust the mean test pressure, p_m, by means of the adjustable flow-control valve.

d) Ensure that the excitation level of the pulse generator is adequate to obtain the correct transfer functions (acceptable coherence criterion > 0,95).

e) If the pump generates a pressure ripple level much greater than the pulse generator, it can be necessary to reduce the pressure ripple level at the pump outlet by means of a hose or other attenuating system. Otherwise, the pressure ripple level of the pump can saturate the dynamic pressure transducers PT1 to PT3 or can prevent accurate measurement of the harmonics of the pressure ripple from the pulse generator.

6.4.2.3 Measurement procedure

For each mean pressure required, capture the inter-transducer transfer functions by signal averaging using a multi-channel analyser allowing the simultaneous acquisition of the output from the three pressure transducers and their transfer function relative to one of the other transducers.

6.4.2.4 Processing of measurements taken

6.4.2.4.1 Determination of the speed of sound in the measuring pipes

Determine the speed of sound in the fluid in accordance with the procedure described in ISO 15086-2, using the measurements from the three pressure transducers PT1 to PT3.

Use the value of the speed of sound, c, to determine the values of the terms A_x and B_x of the pipe sections between transducers PT1 and PT3 and between PT2 and PT3.

6.4.2.4.2 Determination of the impedance of the component connected to the measuring point PT3

Carry out the following using the procedure described in 6.3.

a) Select the pairs of transducers (PT1 and PT3) if the condition of Formula (11) is fulfilled, otherwise select (PT2 and PT3).

$$f < \frac{0{,}7c}{2L_{13}} \tag{11}$$

b) Use the value of the speed of sound, c, as determined in 6.4.2.4.1 to calculate A_1, B_1 or A_2, B_2 and A_e, B_e in accordance with the relationships defined in ISO 15086-1:2001, 5.3.

c) Calculate the transfer functions H_{13} and H_{23}, corrected according to the calibration transfer function.

d) Calculate the inlet hydraulic impedance of the component using Formula (12):

$$Z_{e\to 0} = \frac{-A_x - A_e - B_x H_{x3}}{A_e^2 - B_e^2 + A_e A_x + A_e B_x H_{x3}} \tag{12}$$

where x is either 1 or 2.

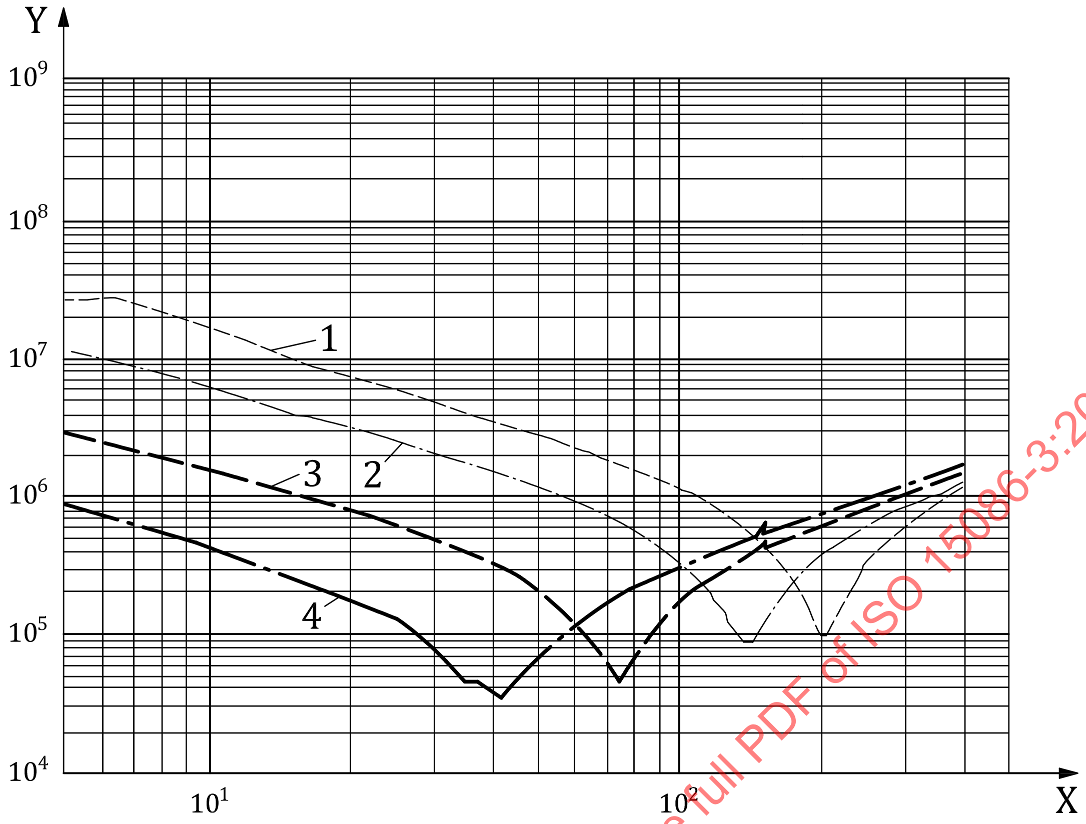
e) Repeat steps a) through d) for all frequencies at which the impedance is determined.

6.4.2.5 Presentation of results

The hydraulic impedance measurements shall be presented in the form of curves as a function of frequency.

As the hydraulic impedance, Z_e, is a complex variable, it is necessary to describe this variable by its real and imaginary parts or by its amplitude and phase.

Examples of representative impedance curves are shown in Figure 4.



Key

X frequency, expressed in hertz (Hz)

Y amplitude of complex hydraulic impedance, Z_e, expressed in pascal seconds per cubic metre (Pa·s·m^{-3})

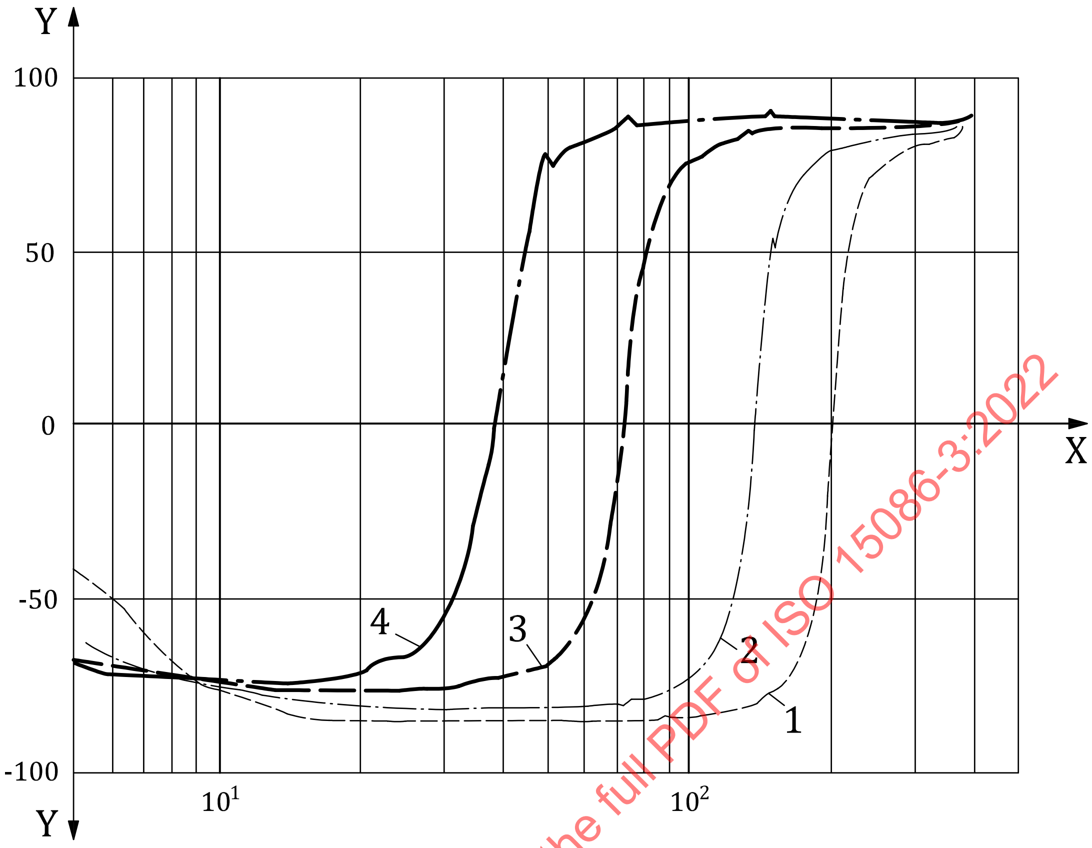
1 curve for p_m = 4 MPa (40 bar)

2 curve for p_m = 2 MPa (20 bar)

3 curve for p_m = 1 MPa (10 bar)

4 curve for p_m = 0,5 MPa (5 bar)

a) Amplitude versus frequency



Key

X frequency, expressed in hertz

Y phase of complex hydraulic impedance, Z_e, expressed in degrees (°)

1 curve for p_m = 4 MPa (40 bar)

2 curve for p_m = 2 MPa (20 bar)

3 curve for p_m = 1 MPa (10 bar)

4 curve for p_m = 0,5 MPa (5 bar)

b) Phase angle versus frequency

Figure 4 — Impedance of a hydraulic accumulator at four mean pressures

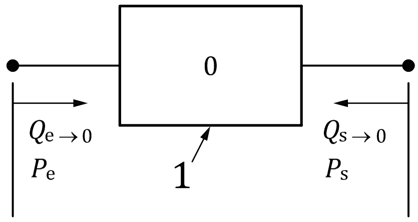
7 Measurement of the admittance matrix and impedance matrix of a two-port passive hydraulic component

7.1 Definitions and principles of measurement of the admittance matrix and impedance matrix of a two-port passive hydraulic component

7.1.1 General

Figure 5 is a schematic diagram of a two-port passive hydraulic connecting component with Fourier transforms of the pressure ripples and Fourier transforms of the flow ripples (P_1, Q_1) and (P_2, Q_2), respectively, at ports 1 and 2.

NOTE 1 A passive component is not itself a generator of hydro-acoustic energy.



Key

1 component 0

Figure 5 — Key parameters for the measurement of admittance matrix and impedance matrix of a two-port component

The hydraulic admittance matrix of the component as shown in Figure 5 can be written as shown in Formula (13):

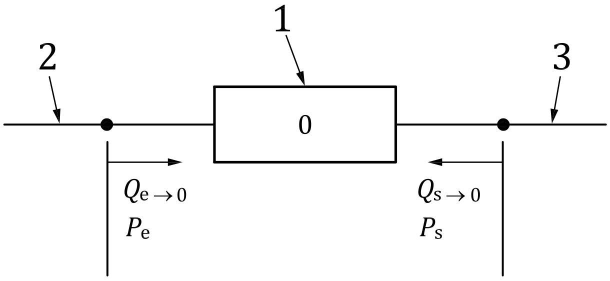
$$\begin{vmatrix} Q_{e\to0} \\ Q_{s\to0} \end{vmatrix} = \begin{vmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{vmatrix} \cdot \begin{vmatrix} P_e \\ P_s \end{vmatrix} \tag{13}$$

where A_{xy} are the terms of the passive component hydraulic admittance matrix.

NOTE 2 Hydraulic admittance is the inverse of the hydraulic impedance.

7.1.2 Principle of the method of measuring the admittance matrix

The inlet and outlet of the component being measured are connected to pipes fitted with dynamic pressure transducers, making it possible to indirectly measure the Fourier transform of the pressure ripples P_e and P_s and the Fourier transform of the flow ripple $Q_{e\to0}$ and $Q_{s\to0}$ (see Figure 6).



Key

1 component 0

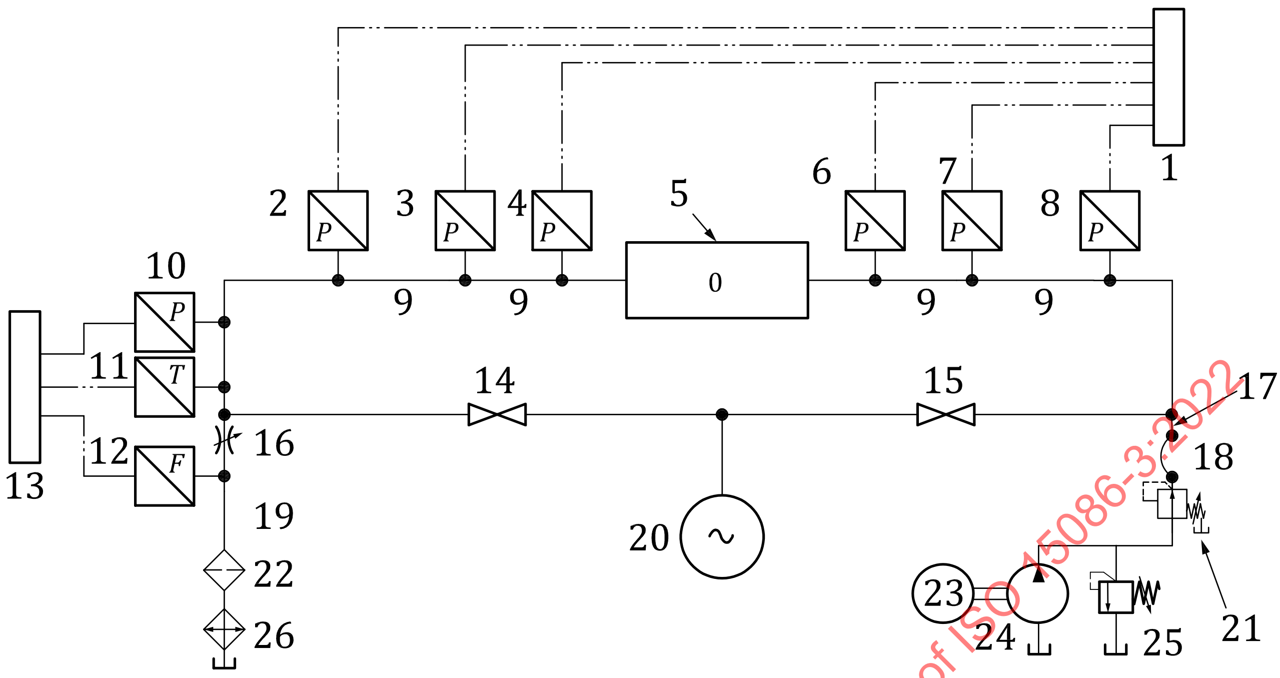
2 pipe in which the pressure ripple and flow ripple are measured, from which the Fourier transform of the pressure ripple, P_e, and Fourier transform of the flow ripple, $Q_{e\rightarrow 0}$, are calculated

3 pipe in which the pressure ripple and flow ripple are measured, from which the Fourier transform of the pressure ripple, P_s, and Fourier transform of the flow ripple, $Q_{s\rightarrow 0}$, are calculated

Figure 6 — Principle of measuring the admittance matrix of a two-port component

Measurement of the admittance matrix consists of determining the values of the matrix terms A_{11}, A_{12}, A_{21} and A_{22} of the hydraulic component under consideration.

Figure 7 shows a more detailed diagram of the test circuit.



Key

1	Fourier analyser	14	shut-off valve
2	pressure transducer PT1	15	shut-off valve
3	pressure transducer PT2	16	adjustable flow-control valve
4	pressure transducer PT3	17	small-diameter pipe
5	component 0	18	flexible hose
6	pressure transducer PT4	19	rigid pipe
7	pressure transducer PT5	20	pulse generator
8	pressure transducer PT6	21	pressure-reducing valve
9	rigid pipes of the same diameter	22	filter
10	pressure transducer to measure mean pressure	23	electric motor
11	thermometer	24	pump
12	flowmeter to measure mean flow	25	pressure-relief valve
13	mean parameters	26	cooler

Figure 7 — Circuit for transfer matrix measurement of a two-port component

The main elements of the test circuit are the following:

a) A hydraulic pump ensures that the mean flow and mean pressure of the component being tested are supplied. The pump shall be protected by means of a pressure-relief valve.

b) A connecting hose connects the pump outlet to the test circuit. If the pump generates a pressure ripple level much greater than the pulse generator, it can be necessary to reduce the pressure ripple level at the pump outlet by means of a hose or other attenuating system. Otherwise, the pressure ripple level of the pump can saturate the dynamic pressure transducers PT1 to PT6 or can prevent accurate measurement of the harmonics of the pressure ripple from the pulse generator.

c) The two pairs of rigid pipes all have the identical internal diameter. The pressure transducers are mounted in these pipes, with the distance between the transducers suited to the band of frequencies used and, for each pair of pipes, the same distances between the transducers and the component.

d) Six pressure transducers (PT1 to PT6) are arranged on rigid pipes upstream and downstream of the component (preferably miniature flush-membrane-type piezoelectric transducers) and used to determine the pressure ripple and flow ripple in the rigid pipes and the speed of sound in the test fluid.

e) A pulse generator, which can be connected to either the upstream pipe or the downstream pipe by means of the isolating shut-off valves, shall be capable of generating pulses in the selected frequency band with an adequate level to obtain the correct signal-to-noise ratio.

f) A pressure-reducing valve allows the adjustment of the mean test pressure, p_m, downstream of the test circuit controlled by the pressure gauge. An adjustable flow-control valve allows the adjustment of the mean test flow rate, q_m, controlled by the flowmeter. In case the mean flow rate, q_m, in the component under test does not influence its hydro-acoustic characteristics, an adjustable flow-control valve is enough for the adjustment of the mean test pressure, p_m.

g) A cooler (heat exchanger) ensures the regulation of the temperature, T_m, of the test fluid controlled by the thermometer.

Solution for the four terms A_{11}, A_{12}, A_{21} and A_{22} of the admittance matrix of the test component requires a system of at least four equations. This requires that tests be performed under two separate conditions. For test condition 1, the pulse generator is connected, by means of the shut-off valves, upstream of the measuring pipes and for test condition 2 the pulse generator is connected, again by means of the shut-off valves, downstream of the measuring pipes.

7.1.3 Algorithm for determining the admittance matrix of a two-port, passive component for identical dimensions of upstream and downstream pipes

7.1.3.1 Overview

The upstream and downstream pipes shall be of the same internal diameter and have identical distances between transducers suited to the frequency bands selected where:

a) L_{23} is the distance between PT2 and PT3;

b) L_{13} is the distance between PT1 and PT3;

c) L_{45} is the distance between PT4 and PT5;

d) L_{46} is the distance between PT4 and PT6;

e) L_{23} is equal to L_{45}; and

f) L_{13} is equal to L_{46}.

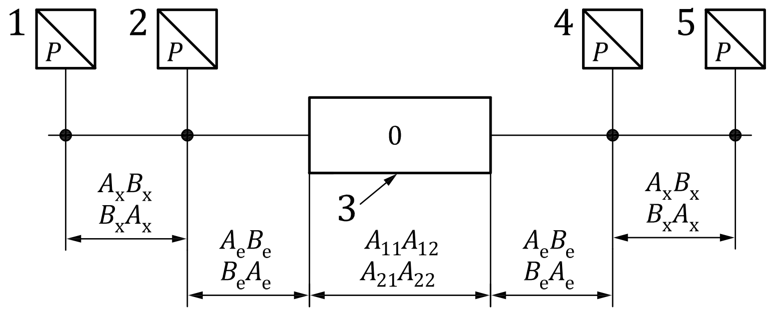
Upstream and downstream fittings shall be of the same diameter and have identical lengths.

The values of the distances L_{23} and L_{13} shall meet the requirements of 6.3.4.2 commensurate with the upper and lower limits of the analysis frequencies.

Determination of the speed of sound in the fluid is necessary to calculate the values of the terms of the admittance matrix A and B of the measuring pipes.

The three upstream transducers PT1, PT2 and PT3 or PT4, PT5 and PT6 allow a determination of the speed of sound in the fluid upstream and downstream of the component in accordance with the requirements of ISO 15086-2.

On the basis of the two different test conditions illustrated in Figure 8, the algorithm for resolving the equation system in 7.1.3.3 c) makes it possible to calculate the admittance matrix terms of the test component.



Key

1 pressure transducer PT1 or PT2
2 pressure transducer PT3
3 component for which the matrix is being determined
4 pressure transducer PT4
5 pressure transducer PT5 or PT6

Figure 8 — Key parameters for the two test conditions

7.1.3.2 Determination of the speed of sound in the measuring pipes

Determine the speed of sound in the fluid in the upstream line in accordance with the procedure described in ISO 15086-2, using the measurements from the three pressure transducers PT1 to PT3. Also use the same procedure to determine the speed of sound in the downstream line using the measurements from the three pressure transducers PT4 to PT6.

Determine the mean speed of sound as the mean of the speeds of sound in the upstream and downstream lines.

7.1.3.3 Determination of the admittance matrix of the component

a) Select the pairs of transducers (PT1 and PT3, PT4 and PT6) if the condition of Formula (11) is fulfilled, otherwise select (PT2 and PT3, PT4 and PT5).

b) Use the value of the mean speed of sound as determined in 7.1.3.2 to determine the values of the terms A_1, B_1 or A_2, B_2 and A_e, B_e according to the relationships defined in ISO 15086-1:2001, 5.3.

c) Calculate the temporary variables X, Y and Z for test condition 1 as given in Formulae (14) to (16) and the temporary variables X', Y' and Z' for test condition 2 according to Formulae (17) to (19) for either $x = 1$ and $y = 6$, or $x = 2$ and $y = 5$:

$$X = \frac{Q_{e\to 0}}{P_e} = -\left[\frac{\left(A_e^2 - B_e^2 + A_e A_x\right) + A_e B_x H_{x3}}{A_x + A_e + B_x H_{x3}}\right] \tag{14}$$

where

$Q_{e\to 0}$ is the Fourier transform of the flow ripple entering the inlet port of the component for test condition 1;

P_e is the Fourier transform of the pressure ripple at the inlet port of the component for test condition 1;

$$H_{x3} = \frac{P_x}{P_3}$$

where P_x and P_3 are the Fourier transforms of the pressure ripples present in the upstream measuring pipe for test condition 1.

$$Y = -\left[\frac{\left(A_e^2 - B_e^2 + A_e A_x\right) H_{43} + A_e B_x H_{y3}}{A_x + A_e + B_x H_{x3}}\right] \tag{15}$$

where

$Q_{s \to 0}$ is the Fourier transform of the flow ripple entering the outlet port of the component for test condition 1;

$$H_{43} = \frac{P_4}{P_3}$$

where P_4 is the Fourier transform of the pressure ripple present in the downstream measuring pipe for test condition 1;

$$H_{y3} = \frac{P_y}{P_3}$$

where P_y is the Fourier transform of the pressure ripple present in the downstream measuring pipe for test condition 1.

$$Z = \left[\frac{\left(A_x + A_e\right) H_{43} + B_x H_{y3}}{A_x + A_e + B_x H_{x3}}\right] \tag{16}$$

NOTE In Figure 7, for test condition 1, BV1 is open and BV2 is closed.

$$X' = \frac{Q'_{e \to 0}}{P'_e} = -\left[\frac{\left(A_e^2 - B_e^2 + A_e A_x\right) + A_e B_x H'_{x3}}{A_x + A_e + B_x H'_{x3}}\right] \tag{17}$$

where

$Q'_{e \to 0}$ is the Fourier transform of the flow ripple entering the inlet port of the component for test condition 2;

P'_e is the Fourier transform of the pressure ripple at the inlet port of the component for test condition 2;

$$H'_{x3} = \frac{P'_x}{P'_3}$$

where P'_x and P'_3 are the Fourier transforms of the pressure ripples present in the upstream and downstream measuring pipes, respectively, for test condition 2.

$$Y' = -\left[\frac{\left(A_e^2 - B_e^2 + A_e A_x\right) H'_{43} + A_e B_x H'_{y3}}{A_x + A_e + B_x H'_{x3}}\right] \tag{18}$$

where

$Q'_{s \to 0}$ is the Fourier transform of the flow ripple entering the outlet port of the component for test condition 2;

$$H'_{43} = \frac{P'_4}{P'_3}$$

