INTERNATIONAL STANDARD

ISO 20155

First edition
2017-08

Ships and marine technology — Test method of flow induced in-pipe noise source characteristics for a ship-used pump

Navires et technologie maritime — Méthode pour déterminer les caractéristiques des sources de bruit induites par l'écoulement dans les tuyaux d'une pompe de navire

Reference number
ISO 20155:2017(E)

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Foreword

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This document was prepared by Technical Committee ISO/TC 8, *Ships and marine technology*, Subcommittee SC 8, *Ship design*.

Introduction

In hydraulic fluid power systems of ships, power is transmitted through a liquid under pressure. Pumps are components that convert rotary mechanical power into hydraulic fluid power. During the process of converting mechanical power into hydraulic power, flow and pressure fluctuations and structure-borne vibrations are generated. These fluid-borne and structure-borne vibrations, which are generated primarily by the unsteady flow produced by the pump, are transmitted through the connected piping system.

The fluid-borne vibration generated by a pump is called pressure ripple or flow induced noise. For pumps used for coolant and drainage in ships, flow induced noise can be transmitted along the piping and radiated into the surrounding water area through a pipe mouth outboard the ship, which produces noise pollution and disturbs the environment including marine mammals.

The level of flow induced noise for a pump depends upon not only the characteristics of the pump itself, but also the circuit in which the pump is installed. Thus, the determination of flow induced noise by a pump is complicated by the interaction between the pump and the circuit. The directly measured data using hydrophones inserted in pipe reaches connecting the pump cannot reflect noise source characteristics of the pump. The method adopted to measure the flow induced noise of a pump should be such as to eliminate the interaction.

ISO 10767-1 and ISO 10767-2 provide the test methods for the positive displacement pump with the precision and simplified method, respectively, where the pump is treated as a single port acoustic source and its source characteristics expressed by two parameters of source strength as well as source impedance can be obtained. For other common pumps with two ports, the sound field between the inlet and outlet of a pump is inter-coupling, source characteristics cannot be fully expressed by two parameters, but expressed by up to six parameters, i.e. source pressures at the inlet and outlet of a pump and four elements in a 2 × 2 impedance matrix. There is a need to establish a new standard about a test method for noise source characteristics of a pump, based on two-port acoustic source model.

The source characteristics of flow induced noise are used for evaluating the hydrodynamic noise feature of the pump. The measured results can be compared for pumps of different types and manufacture. This will enable the pump designer to evaluate the effects of design modifications and help hydraulic system designers to avoid selecting pumps having high noise levels.

The method is based upon the application of plane wave transmission line theory to the analysis of noise propagation in hydraulic systems. By adopting a two-port model with noise source and evaluating the impedance characteristics of the pump using a secondary-source method, it is possible to obtain the source strength of the pump, independent of the circuit that the pump locates.

Ships and marine technology — Test method of flow induced in-pipe noise source characteristics for a ship-used pump

1 Scope

This document specifies a test method for determining flow induced in-pipe noise source characteristics of a ship-used pump as a two-port sound source in laboratory conditions by measuring acoustic pressures in the pipe reaches of inlet and outlet.

The test method is applicable to all types of centrifugal pumps with a diameter over 50 mm operating under steady conditions.

The suitable frequency range of the test method is about 10 Hz to 1 000 Hz, and the upper frequency is dependent on the inner diameter of the pipe, in which the plane acoustic wave propagates.

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 10767-1:2015, *Hydraulic fluid power — Determination of pressure ripple levels generated in systems and components — Part 1: Method for determining source flow ripple and source impedance of pumps*

IEC 60565, *Underwater acoustics — Hydrophones — Calibration in the frequency range 0,01 Hz to 1 MHz*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

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

3.1
two-port source
test object with inlet and outlet which are inter-coupling acoustically

3.2
passive characteristic
acoustic characteristic of a test object only acting as a transmission path, which can be indicated by different manners such as a transfer matrix, impedance matrix, scattering matrix, etc.

3.3
active characteristic
acoustic characteristic of a test object which provides acoustic energy into a piping system

Note 1 to entry: Depending on the adopted theoretical model, active characteristics can be represented by acoustic pressure source, volume velocity source, etc.

3.4
test section
pipe reaches which are used to fix the hydrophones, measuring the in-pipe noise from the acoustic source

3.5
static pressure in pipe
fluid pressure in pipe as fluid is in still, which is one of the parameters describing the working conditions of the test object

3.6
working flowrate
fluid volume or mass per unit time, which is one of the working parameters of the test object

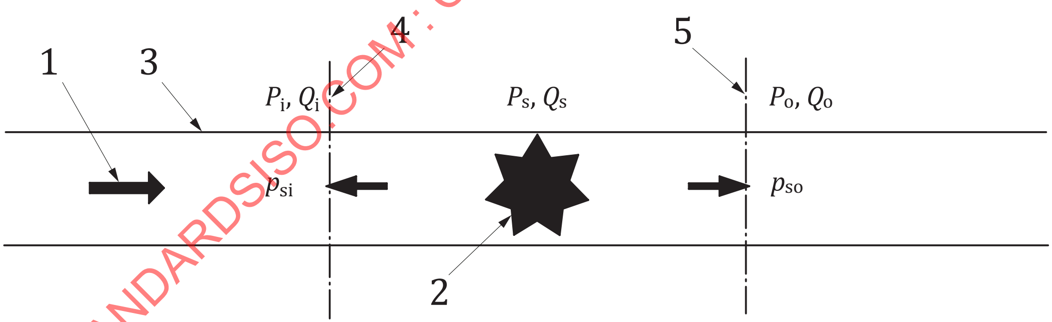
3.7
pressure drop/hydraulic loss
static pressure difference between the inlet and outlet as the fluid passes through the test object, which is a reference parameter for analysis use

3.8
foundation
platform built by ferroconcrete, used to install the experimental facility and test objects, including ground basis, guide rail for convenient mount of pipeline

4 Two-port source model and test method of source characteristic of pump

4.1 Two-port source model of a pump

It is assumed that only plane wave would transmit in the pipeline, and the noise source characteristic of a pump could be described by linear superposition of active and passive characteristic. Based on the electro-acoustic analogy and acoustic transmission line theory, there are three different models to characterize a two-port source, which can be called "Transmission model", "Impedance model" and "Scattering model". They are illustrated in Annex A.



Key
1 flow
2 source
3 pipe
4 inlet
5 outlet

Figure 1 — Two-port noise source model

Adopting the impedance model, the radiating sound from the inlet and outlet into pipe can be expressed by Formula (1):

$$\begin{pmatrix} P_o \\ P_i \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} Q_o \\ Q_i \end{pmatrix} + \begin{pmatrix} P_{so} \\ P_{si} \end{pmatrix} = \boldsymbol{Z} \begin{pmatrix} Q_o \\ Q_i \end{pmatrix} + \begin{pmatrix} P_{so} \\ P_{si} \end{pmatrix} \tag{1}$$

where

P_s, Q_s is the real sound source of a pump providing sound pressure and volumetric velocity into the inlet and outlet of the pump, while the connected pipes are unlimited or anechoic;

P_o, Q_o is the sound pressure and volumetric velocity at the outlet of acoustic source, respectively;

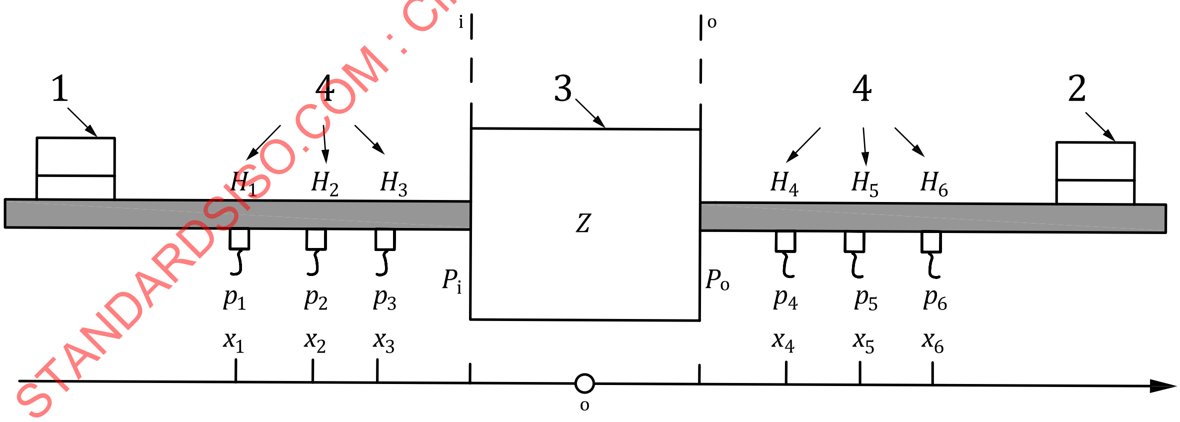
P_i, Q_i is the sound pressure and volumetric velocity at the inlet of acoustic source, respectively;

P_{so}, P_{si} is the sound pressure source which indicate radiating sound from the inlet and outlet into pipe;

Z is the impedance matrix, $Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$.

4.2 Test methods for source characteristic parameters of the pump

Using the secondary-source method, turn on the secondary acoustic source on one side (inlet or outlet), get and register signals from the four hydrophones. Then, move it to another side and turn it on, register signals of the four hydrophones again. By this procedure, matrix parameter Z can be derived. Finally, turn off the source, active characteristic parameters p_s and q_s of the pump can be obtained utilizing the result of matrix parameter Z.



Key

1 secondary source 1

2 secondary source 2

3 test pump

4 hydrophones H_1 to H_6

Figure 2 — Sketch of dual-position acoustic source methods

In Figure 2, H_1 to H_6 are six hydrophones along the pipe mounted at positions x_1 to x_6, correspondingly.

The procedure for measuring source characteristics is given as follows.

a) Turn on the secondary acoustic source at the inlet for the following result:

$$\begin{pmatrix} P_o^{(1)} \\ P_i^{(1)} \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} Q_o^{(1)} \\ Q_i^{(1)} \end{pmatrix} \tag{2}$$

where superscript $^{(1)}$ indicates the corresponding quantities obtained by turning on the secondary sound source at the first time, and they can be obtained by means of calculation using formulae in Annex B, which correlate the quantities with the measured signals from hydrophones.

b) Turn on the secondary acoustic source at the outlet for the following result:

$$\begin{pmatrix} P_o^{(2)} \\ P_i^{(2)} \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} Q_o^{(2)} \\ Q_i^{(2)} \end{pmatrix} \tag{3}$$

where superscript $^{(2)}$ indicates the corresponding quantities obtained by turning on the secondary sound source at the second time.

c) Combine Formulae (2) and (3) and solve the equation system, the impedance matrix Z can be calculated.

$$\begin{pmatrix} P_o^{(1)} & P_o^{(2)} \\ P_i^{(1)} & P_i^{(2)} \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} Q_o^{(1)} & Q_o^{(2)} \\ Q_i^{(1)} & Q_i^{(2)} \end{pmatrix} \tag{4}$$

d) Turn off the secondary acoustic source, and let the measured pump operate under the needed conditions, the active source parameters, i.e. sound pressure source P_{so}, P_{si} can be obtained according to Formula (5).

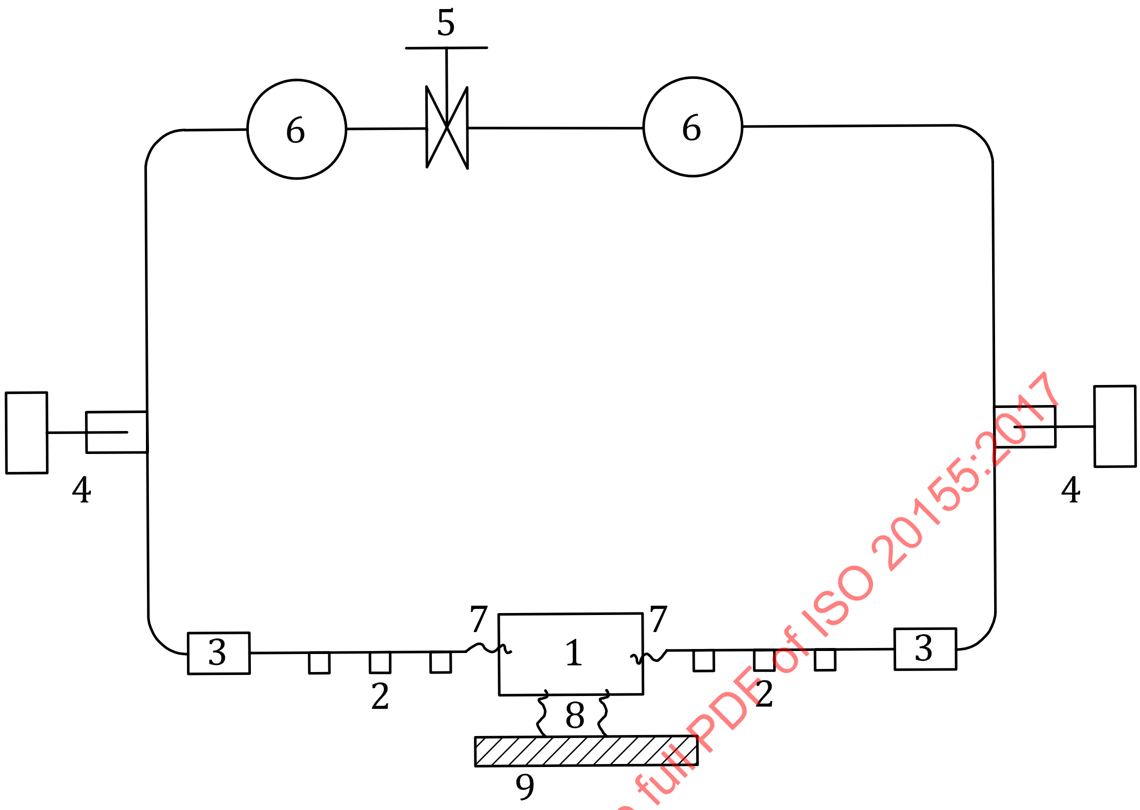
$$\begin{pmatrix} P_{so} \\ P_{si} \end{pmatrix} = \begin{pmatrix} P_o \\ P_i \end{pmatrix} - \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} Q_o \\ Q_i \end{pmatrix} \tag{5}$$

At the right side of Formula (5), P_o, P_i and Q_o, Q_i are obtained by calculation using the measured signals from hydrophones during pump operation.

5 Test rig

5.1 Test loop

Figure 3 shows the schematic of test circuit of flow induced in-pipe noise source characteristic of the pump.



Key

1 pump
2 hydrophone
3 vibration
4 secondary acoustic excitor
5 throttling valve
6 water tank
7 flexible insertion
8 vibroisolator
9 foundation

Figure 3 — Sketch of test circuit for measuring flow-noise source characteristic of the pump

In the schematic diagram, a water tank is used for separating sound waves from the inlet and outlet of pump. A throttling valve is used for flowrate adjustment and located between the water tanks for reducing the effect on source characteristic measurement of the pump. A secondary acoustic exciter can provide an external acoustic source for determination of passive features of the pump, and the vibration damper can suppress the vibration of the test section from the neighbouring pipe reaches. Hydrophones are mounted in test sections at the inlet and outlet of the pump for measuring the acoustic pressure in the pipeline.

5.2 Installation of test pump

The test pump should be installed as recommended by the manufacturer and mounted in such a manner that the response of the mounting-to-pump vibration is minimized.

In order to reduce vibration disturbance from the ground and the connected pipe, the pump should be installed on the foundation through vibration isolators and connected to the pipeline with flexible insertions. The isolators and flexible insertions should be chosen close to the actual conditions.

The prime mover and associated drive couplings shall not generate torsional vibration in the pump shaft. If necessary, the pump and the driving unit shall be isolated from each other to eliminate vibration generated by the prime mover.

5.3 Ground foundation and supporting structure

Ground foundation should be made of reinforced concrete and isolated to the surrounding ground in the laboratory such as foundations of other auxiliary equipment. A supporting structure of the pipeline is also required to be rigidly connecting the pipeline with the ground foundation.

5.4 Test-bed pipeline

The pipeline shall be composed of uniform, rigid, straight metal pipes at each port of the pump.

The inner diameters of the test pipeline at inlet and outlet should be equal to that of the inlet and outlet of the test pump respectively. In the case of the inequality of inner diameter between the test pump and pipeline, the adaptor connecting the pump ports to the pipe shall have an internal diameter which does not differ from the pipe diameter by more than 10 % at any point. Any such variations in internal diameter shall occur over a length not exceeding twice the internal diameter of the pipe. The adaptor shall be arranged in order to prevent the formation of air pockets in it.

The bending section in the pipeline of Figure 3 shall adopt bends with bending radii larger than twice the radii of the pipe to reduce hydrodynamic noise arising from the flow over it.

The total length of the uniform straight pipeline in front of the inlet flange of the test pump should be 10 times larger than pipe diameter.

5.5 Test section

Each of the two test sections as a straight pipe reach is fixed on the inlet and outlet of the test pump respectively, with the length more than 2 m, the inner diameters, D, equal to that of inlet and outlet pipe of the test pump. The test section should be fabricated with a tube of wall thickness greater than 5 % of the inner diameters, D. In the test section, two or three hydrophones with equal interval are fixed on the pipe. Each hydrophone is put in a plug mounted on the pipe. In order to reduce interference from turbulence over the inner wall of the pipe, the hydrophones shall be mounted such that their diaphragms are flush with the inner wall of the pipe to within ±0,5 mm. The sealing ring in the plug should be used between the hydrophone and plug body to prevent water leakage.

The distance between two or two of three hydrophones depends on the maximum frequency of the measurement frequency range and shall be given by Formula (6), to within 1 %:

$$x_2 - x_1 = \frac{\sqrt{B_{\mathrm{eff}} \times 10^5 / \rho}}{(67 \times f_{0,\max})} \tag{6}$$

where

$f_{0,\max}$ is the maximum frequency of the measurement frequency range, in hertz;

B_{eff} is the effective bulk modulus, in bars;

ρ is the density, in kilograms per cubic meter.

Meanwhile, in order to avoid turbulent fluctuation pressure from the pump impacting directly on hydrophone, the nearest hydrophone should be positioned at a distance larger than 3 to 5 times pipe inner diameter from the test pump.

5.6 Throttling valve

The throttling valve should meet the need of flowrate adjustment. From the point of acoustic measurement, it should have a low noise level and no cavitation should appear under the test working conditions.

5.7 Secondary acoustic exciter

The secondary acoustic exciter is composed of a vibration exciter of electromagnetic type and a piston with a bar connecting them. The piston is driven by the exciter and produces acoustic plane waves by its oscillatory motion in the working medium. The intensity of acoustic waves should be 10 dB higher than the background noise in the frequency spectrum to ensure sufficient signal-noise-ratio.

5.8 Water tank

A water tank should have a volume at least 30 times the connected pipeline.

6 Instrumentation

6.1 General

The source characteristic test of a pump includes a static and dynamic measurement. A static measurement is mainly used to define working parameters of the pump. A dynamic measurement is used to collect sound pressure signals generated by the test pump radiating into the pipeline.

6.2 Static measurements

In static measurement, some quantities should be measured, which include flowrate and static pressure of fluid in the pipe, shaft rotational speed of pump and pressure drop across the pump, temperature of working medium, etc.

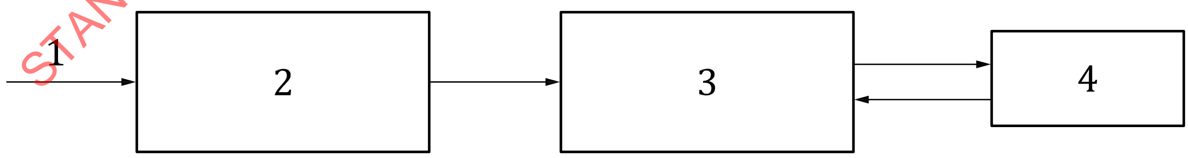
The requirement of instrumentation for static measurements shall be in accordance with ISO 10767-1:2015, 4.1.

6.3 Dynamic measurements

The instruments for dynamic measurements consist of a transducer, a signal conditioner and data acquisition or signal analyser. A hydrophone is used to measure the sound pressure in the pipe. A charge amplifier or measuring amplifier is chosen as a signal conditioner.

Transducers shall be chosen to meet the requirements for working in the allowable environment (such as static pressure, temperature, magnetic field, anti-corrosion, etc.) and needed frequency range. The natural frequency of the hydrophone shall be higher than 30 kHz and nonlinearity less than ±1 %. In the test frequency range, the amplitude inhomogeneity of hydrophone should be less than 0,2 dB, and the inhomogeneity of phase frequency characteristic less than 0,5°.

Figure 4 shows the schematic diagram of dynamic measurement system.



Key

1 hydrophone

2 charge/measuring amplifier

3 data acquisition or signal analyser

4 computer

Figure 4 — Schematic diagram of dynamic measurement system

A Piezoelectric mini-type hydrophone can be adopted. The hydrophone outputs the charge, which is imported into the data acquisition or signal analyser. With the computer, a signal can be recorded and analysed. Using the post-processing analysis software, final results can be obtained.

Hydrophones shall be calibrated in accordance with the requirements of IEC 60565.

7 Test preparation

A test circuit should be assembled with a layout shown in Figure 3. Each component of a test circuit shall be chosen, designed, and mounted according to requirements described in Clause 5.

Each two or three hydrophones shall be installed in the test section located at the inlet and outlet of the test pump. Before installation, the exterior surface of the hydrophone shall be soaked and wetted in a soap liquid, in order to avoid air bubbles sticking to the surface of the hydrophones. Fill the pipeline system with a working medium (ordinarily water).

Test conditions for fluid as working medium in pipeline should be met or known according to ISO 10767-1:2015, Clause 6 and 7.3.

After the pipeline of the test circuit is full of the working medium, turn on the test pump with low rotation speed for gathering air to the top of the water tank, open the drain tap in a pipe connected to the water tank for discharging air from the working medium. Repeat the process of filling the water and exhausting the gas operation several times, then keep the test circuit in place for 12 h. The test can be started until no bubbles exists in the working medium. Other methods for exhausting the gas can also be recommended, such as using a vacuum pump for extracting air.

While connecting all the instruments and adjusting the instruments, make sure that the instruments are ready for testing.

8 Test procedure

The test shall be performed in accordance with the following procedure.

a) Measure the background noise by collecting signals from hydrophones from the test section. In this case, the test pump does not work and no interference of vibration and noise from the surrounding environment affects the test.

b) Turn on the secondary acoustic exciter upstream of the test pump to generate white noise in the pipeline. Collect signals from each transducer mounted on two of the test sections, then turn off the acoustic exciter.

c) Turn on the acoustic exciter downstream of the test pump to generate white noise in the pipeline. Collect signals from each transducer mounted on two of the test sections, then turn off the acoustic exciter.

d) Adjust the opening of throttling valve, make sure the test pump would produce the required flowrate in the test circuit. Turn on the test pump and stabilize it for 5 min, measure and record the flowrate, static pressure, rotation speed of pump. Collect signals from each transducer mounted on two of the test sections.

e) Change working condition (for example, static pressure in pipe or rotate speed of pump) in accordance with the test requirements. Repeat step d).

9 Data processing

9.1 General

Before data processing for obtaining the passive and active characteristics of a pump as flow induced noise source, it is necessary to check whether the signal-noise-ratio (SNR) of the measured results from the test procedure is sufficient. SNR refers to a comparison of signals from each of the hydrophones when the secondary source or the pump is switched on, with the measured background noise. SNR should be higher than 10 dB over the whole frequency range of measurement.

If the pipeline in the test circuit is not mounted rigidly and is not well vibration-isolated from the test pump, the effect of interference from pipe vibration on the test results should be assessed according to the method in Annex C. When the pump or workshop is very noisy, the effect of interference from airborne noise on the test results should also be assessed according to the method in Annex C.

If the SNR is sufficient and the effect of interference is negligent, data processing can turn to the next step, i.e. obtaining passive and active characteristics of the test pump.

9.2 Passive characteristic of noise source

The passive characteristic matrix of the noise source can be evaluated by the collected data in steps b) and c) of the test procedure (see Clause 8).

The formulae for determining the passive characteristic of noise sources are given in Annex D.

9.3 Active characteristic

The positive characteristic of the acoustic source can be calculated by the collected data in step d of the test procedure.

The formulae for determining active characteristics of noise sources are given in Annex E.

10 Evaluation criteria for the test result

To make the test result effective, the effect of pipeline vibration and airborne noise of the test pump on the test results of flow induced noise should be evaluated according to Annex C.

Verification of the test method given in this document was carried out for a T-shaped sound excitor as a reference acoustic source, for which the source characteristics could be obtained from theoretical derivation and compared with test results. This example for verification is illustrated in Annex F.

Another evaluation criteria for the test result is based on measurement uncertainty analysis. The overall measurement uncertainty is evaluated on a combination of components which describe random errors (where the uncertainty may be estimated from the measurement repeatability) and errors caused by the effects that may introduce systematic bias into the measurements.

The results of uncertainty analysis for test of source characteristics of a pump are listed in Table 1 and Table 2. From Table 1 and Table 2, the total measurement uncertainty would be less than 3 dB.

Table 1 — Components of measurement uncertainty for source characteristics of a pump

Components	Symbols	Source of uncertainty	Relative uncertainty	Type of error
Measurement of sound pressure and its transfer function	u_{H1}	Non-homogeneity of amplitude-frequency of hydrophone	0,008 7	Systematic error
	u_{H2}	Non-homogeneity of amplitude-frequency of pre-amplifier	0,011 5	
	u_{H3}	Maximal allowable error of data collector	0,005 8	
	u_N	Random effect	0,3	
	$u_{1\text{rel}}$	Sound pressure	0,015 5	
	$u_{2\text{rel}}$	Transfer function of sound pressure	0,300 4	
Determination of impedance matrix	$u_{31\text{rel}}\left(\lvert Z \rvert\right)$	Dynamic change of static pressure	0,2	Random error
Sound pressure source	$u_{31\text{rel}}\left(\lvert P_s \rvert\right)$	Dynamic change of static pressure	0,018 82	
	$u_{32\text{rel}}\left(\lvert P_s \rvert\right)$	Dynamic change of flowrate	0,052	
	$u_{33\text{rel}}\left(\lvert P_s \rvert\right)$	Dynamic change of rotation speed	0,056 79	
	$u_{31\text{rel}}\left(\lvert P_s \rvert\right)$		0,079	
Total relative uncertainty: $u_{\text{crel}}(P_s)=\sqrt{\left(\frac{u(\lvert Z\rvert)}{\lvert Z\rvert}\right)^2+\left(\frac{u(\lvert p\rvert)}{\lvert p\rvert}\right)^2+\left(\frac{u(\lvert H_{p/\text{pre}}\rvert)}{\lvert H_{p/\text{pre}}\rvert}\right)^2}, =\sqrt{u_{1\text{rel}}^2+u_{2\text{rel}}^2+u_{3\text{rel}Z}^2+u_{3\text{rel}P}^2}$			0,37	

Table 2 — Measurement uncertainty of source characteristics of a pump under 95 % confidence probability

Parameter	Uncertainty under 95 % confidence probability	
	Value	Decibel
Sound pressure source	0,74	2,4

11 Test report

11.1 Overview

The following information shall be compiled and recorded in a test report.

11.2 General information

a) name and address of pump manufacturer and, if applicable, the user;

b) reference number(s) for identification of the pump;

c) name and address of persons or organization responsible for tests on the pump;

d) date and place of tests;

e) conformance statement.

11.3 Test record

a) Description of pump:

   1) rating flowrate of the pump;

   2) rating lift of the pump;

   3) rating output power of electric motor;

   4) shaft rotational speed of electric motor;

   5) diameter of inlet and outlet port of the pump.

b) Mounting and installation conditions of pump:

   1) description of pump mounting conditions;

   2) nature and characteristics of the hydraulic circuit;

   3) details of any vibration isolation treatment.

c) Instrumentation:

   1) class of measurement;

   2) details of equipment used to monitor pump operating conditions, including type, serial number and manufacturer;

   3) details of equipment used to measure in-pipe noise, including type, serial number and manufacturer;

   4) details of secondary source;

   5) bandwidth of frequency analyser.

11.4 Test result

a) Record of pump operating conditions:

   1) type of fluid;

   2) temperature of fluid at pump inlet;

   3) mean inlet pressure;

   4) mean outlet pressure or hydraulic loss between inlet and outlet;

   5) mean pump delivery flow.

b) Noise source characteristics:

   1) source pressure from inlet;

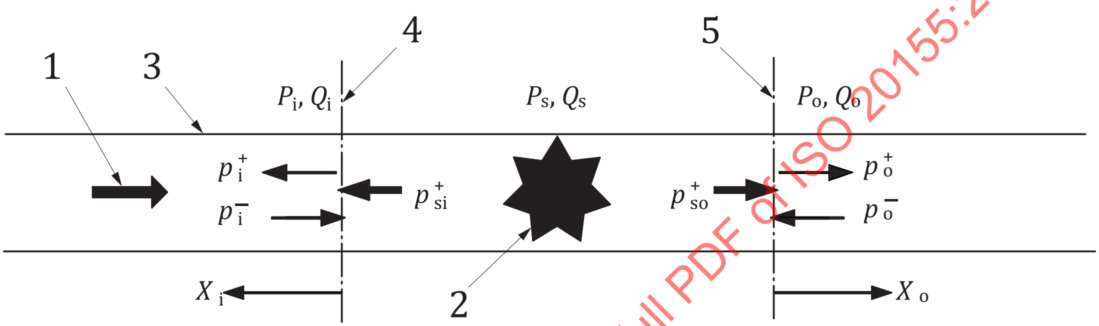
   2) source pressure from outlet;

3) each elements of impedance matrix, including amplitude and phase.

Annex A
(informative)

Theoretical models of a two-port source and transformation mutually between matrix *Z*, *S*, *T*

There are three models to characterize a two-port source, which use different physical quantities describing the relation between one port and another port, and have different physical significance correspondingly. They are classified as “Transmission model”, “Impedance model” and “Scattering model”.



Key

1 flow
2 source
3 pipe
4 inlet
5 outlet

Figure A.1 — Two-port source model

In Figure A.1, all the symbols are defined as follows:

P_o ,Q_o	the sound pressure and volumetric velocity at the outlet of acoustic source, respectively;
P_i ,Q_i	the sound pressure and volumetric velocity at the inlet of acoustic source, respectively;
p_o^+ ,p_o^-	the acoustic wave transferring in positive and negative direction at the outlet;
p_i^+ ,p_i^-	the acoustic wave transferring in positive and negative direction at the inlet;
P_s ,Q_s	the sound pressure and volumetric velocity source, which are active source parameters in the sound transmission model;
P_{so} ,P_{si}	the sound pressure source at the inlet and outlet in the impedance model;
p_{si}^+, p_{so}^+	the radiation sound pressure from source to inlet and outlet in the scattering model.

Transmission model:

$$\begin{pmatrix} P_o \\ Q_o \end{pmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{pmatrix} P_i \\ Q_i \end{pmatrix} + \begin{pmatrix} P_s \\ Q_s \end{pmatrix} = \boldsymbol{T} \begin{pmatrix} P_i \\ Q_i \end{pmatrix} + \begin{pmatrix} P_s \\ Q_s \end{pmatrix} \tag{A.1}$$

Impedance model:

$$\begin{pmatrix} P_o \\ P_i \end{pmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{pmatrix} Q_o \\ Q_i \end{pmatrix} + \begin{pmatrix} P_{so} \\ P_{si} \end{pmatrix} = \boldsymbol{Z} \begin{pmatrix} Q_o \\ Q_i \end{pmatrix} + \begin{pmatrix} P_{so} \\ P_{si} \end{pmatrix} \tag{A.2}$$

Scattering model:

$$\begin{pmatrix} p_o^+ \\ p_i^+ \end{pmatrix} = \begin{bmatrix} r_o & \tau_i \\ \tau_o & r_i \end{bmatrix} \begin{pmatrix} p_o^- \\ p_i^- \end{pmatrix} + \begin{pmatrix} p_{so}^+ \\ p_{si}^+ \end{pmatrix} = \boldsymbol{S} \begin{pmatrix} p_o^- \\ p_i^- \end{pmatrix} + \begin{pmatrix} p_{so}^+ \\ p_{si}^+ \end{pmatrix} \tag{A.3}$$

where T, Z and S are transfer matrix, impedance matrix and scattering matrix, respectively, which indicate the passive characteristic of acoustic source.

The three matrixes, Z, S and T, can be transformed mutually and the transformation relationship from T to Z and S is given by Formulae (A.4) and (A.5):

$$\boldsymbol{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \frac{1}{T_{21}} \begin{bmatrix} T_{11} & -(T_{11}T_{22} - T_{12}T_{21}) \\ 1 & -T_{12} \end{bmatrix}, \begin{pmatrix} p_{so} \\ p_{si} \end{pmatrix} = \begin{pmatrix} P_s - \dfrac{T_{11}}{T_{21}} Q_s \\ -\dfrac{1}{T_{21}} Q_s \end{pmatrix} \tag{A.4}$$

$$\boldsymbol{S} = \begin{bmatrix} r_o & \tau_i \\ \tau_o & r_i \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} \Delta_1 & \Delta_2 \\ \Delta_3 & \Delta_4 \end{bmatrix}, \begin{pmatrix} p_{so}^+ \\ p_{si}^+ \end{pmatrix} = \begin{pmatrix} (P_s + Q_s Z_o)/2 \\ (Q_s Z_o - P_s)/\Delta \end{pmatrix} \tag{A.5}$$

In which:

$$\begin{aligned} &\Delta = T_{11} - T_{12}/Z_i - Z_o T_{21} + T_{22}\frac{Z_o}{Z_i} \\ &\Delta_1 = T_{11} - T_{12}/Z_i + Z_o T_{21} - T_{22}\frac{Z_o}{Z_i} \\ &\Delta_2 = (\Delta_3 * \Delta_1 + \Delta_4)/2; \Delta_3 = Z_o T_{21} + T_{22}\frac{Z_o}{Z_i} - T_{11} - T_{12}/Z_i \\ &\Delta_4 = T_{11} + T_{12}/Z_i + Z_o T_{21} + T_{22}\frac{Z_o}{Z_i} \end{aligned} \tag{A.6}$$

Annex B
(informative)

Evaluation of quantities at inlet and outlet ports

Based on the assumption of plane wave propagating in the pipe, sound pressure, P, and volume speed, Q, at any point x satisfy the following relations:

$$P(x) = Ae^{-ikx} + Be^{ikx} \tag{B.1}$$

$$Q(x) = \frac{F}{z_0}(Ae^{-ikx} - Be^{ikx}) \tag{B.2}$$

where

k	is the wavenumber, $k = \frac{\omega}{c} = \frac{2\pi f}{c}$;
ω	is the circular frequency;
f	is the frequency;
F	is the inner cross section area of pipe;
$z_0 = \rho_0 c_0$	is the characteristic acoustic impedance of working medium;
ρ_0	is the density of fluid;
c, c_0	is the sound speed of working medium in pipe and in infinite field, respectively.

When two hydrophones are inserted in each test section (see Figure 2), c and c_0 are correlated by Formula (B.3):

$$c = \frac{c_0}{\sqrt{1 + (\rho_0 c_0^2) d / (Eh)}} \tag{B.3}$$

where

d	is the inner diameter of pipe;
h	is the thickness of pipe wall;
E	is the Young's modulus of pipe material;

In this case, coefficient A and B in Formulae (B.1) and (B.2) can be determined by means of the measured value of sound pressure p_1 and p_2 at point 1 and 2, correspondingly, P_i, Q_i and P_o, Q_o can be evaluated by Formulae (B.4) and (B.5):

$$P_i = \frac{p_2 \sin(kl_1) - p_1 \sin[k(l_1 - s)]}{\sin(ks)}, P_o = \frac{p_4 \sin(kl_2) - p_3 \sin[k(l_2 - s)]}{\sin(ks)} \tag{B.4}$$

$$Q_i = -\frac{F}{z_0} \frac{p_2 \cos(kl_1) - p_1 \cos[k(l_1 - s)]}{j \sin(ks)}, Q_o = -\frac{F}{z_0} \frac{p_4 \cos(kl_2) - p_3 \cos[k(l_2 - s)]}{j \sin(ks)} \tag{B.5}$$

where

l_1, l_2 is the distance from inlet (output) to p_1 (p_3), respectively;

s is the interval of two hydrophones, which should meet the requirement : $0{,}1 < fs / c < 0{,}4$.

When three hydrophones are used in each test section (see Figure 2), c can be measured according to signals from those hydrophones. With equal interval s between the neighbouring hydrophones, c in the pipe of inlet is derived by Formula (B.6):

$$k = \frac{c}{\omega} = \frac{1}{s} ar\cos\left(\frac{p_1 + p_3}{2p_2}\right) \tag{B.6}$$

Similarly for c in the pipe of outlet.

By means of the measured value of sound pressure p_1, p_2 and p_3, coefficient A and B in Formulae (B.1) and (B.2) can be obtained:

$$A = \frac{3\lambda_3 - \lambda_4\lambda_1}{9 - \lambda_2\lambda_4}, B = \frac{3\lambda_1 - \lambda_2\lambda_3}{9 - \lambda_2\lambda_4} \tag{B.7}$$

where

$\lambda_1 = p_1 + e^{jkS_1} p_2 + e^{jkS_2} p_3$, $\lambda_2 = 1 + e^{2jkS_1} + e^{2jkS_2}$;

$\lambda_3 = p_1 + e^{-jkS_1} p_2 + e^{-jkS_2} p_3$, $\lambda_4 = 1 + e^{-2jkS_1} + e^{-2jkS_2}$;

$s_1 = 2s_2 = 2s$.

Inserting A and B into Formulae (B.1) and (B.2), P_i, Q_i and P_o, Q_o can be evaluated.

Annex C
(informative)

Judgment of effectiveness for the test

C.1 Effect of pipeline vibration on the results of hydrodynamic noise

When the pump does not work and the test system is stopped, hydrophones are installed in the test section of the pipeline system, which is filled with water medium. Vibration excitation is carried out with the exciter over the hydrophone test section. Acceleration transducers are installed along the axial direction on the casing of hydrophone, and the signal from hydrophones and accelerations are measured at the same time.

Determine the sensitivity of the hydrophone when the hydrophone is influenced by the pipeline vibration, as shown in Formula (C.1):

$$\Delta_a^n = L_{\mathrm{p,vib}}^n - L_{\mathrm{(excite)}}^n, (n=1,2,3,4,5,6), \mathrm{dB} \tag{C.1}$$

where

Δ_a^n	is the vibration sensitivity of each hydrophone in the test section, which influenced by pipeline vibration;
$L_{\mathrm{p,vib}}^n$	is the measuring result of each hydrophone in the test section as the pipe is excited by external exciter;
$L_{\mathrm{(excite)}}^n$	is the measuring result of vibration at the casing of each hydrophone in the test section as the pipe is excited by external exciter.

When the pump is running under test conditions, measure the vibration acceleration level of the pipe section where each hydrophone is located. While measuring the sound pressure of the pump sound source, calculate the hydrodynamic noise interference level caused by the pipe wall vibration, as shown in Formula (C.2):

$$L_{\mathrm{p,vib}}^{n,run} = L_{\mathrm{vib}}^n + \Delta_a^n, \mathrm{dB} \tag{C.2}$$

Check whether the vibration interference level is lower than direct measured hydrodynamic noise level 10 dB or not. If measurement frequency meets this condition, it can be considered that the influence of the pipeline vibration caused by the opening pump on the results can be ignored.

C.2 Effect of airborne noise on the results of hydrodynamic noise

When the pump does not work and the test system is stopped, broadband airborne noise excitation is applied near the test section in the measurement frequency band.

At the distance of 1 m to 2 m from measuring points 2 and 5 in the middle of the test section and 1m from ground, measure airborne noise level, $L_{\mathrm{air(excite)}}^2$.

Measure hydrodynamic noise level at the same time.

Determine the coupling coefficient of airborne noise and hydrodynamic noise, K_p:

$$K_{\mathrm{p}}^{H1} = L_{\mathrm{p,air}}^{\max 1,2,3} - L_{\mathrm{air(excite)}}^{2}\text{, dB} \tag{C.3}$$

$$K_{\mathrm{p}}^{H2} = L_{\mathrm{p,air}}^{\max 4,5,6} - L_{\mathrm{air(excite)}}^{5}\text{, dB} \tag{C.4}$$

where

K_{p}^{H1} is the coupling coefficient of airborne noise level in the test section No.H1 and the maximal hydrodynamic noise level caused by it;

K_{p}^{H2} is the coupling coefficient of airborne noise level in the test section No.H2 and the maximal hydrodynamic noise level caused by it;

$L_{\mathrm{p}}^{\max 1,2,3}$ is the maximal hydrodynamic noise level of the measurement results in each 1/3 octave band of measuring point 1,2 and 3 in the test section No.H1, when pipe is anthropogenic excitation by airborne noise of external sound source;

$L_{\mathrm{p}}^{\max 4,5,6}$ is the maximal hydrodynamic noise level of the measurement results in each 1/3 octave band of measuring point 4,5 and 6 in the test section No.H2, when pipe is anthropogenic excitation by airborne noise of external sound source.

When the pump is running under the work conditions, measure airborne noise level L_{air}^{2} and L_{air}^{5}.

Calculate the interference level caused by airborne noise during the measurement of the sound pressure of the pump sound source:

$$L_{\mathrm{p}}^{n,H1,run} = L_{\mathrm{air}}^{2} + K_{\mathrm{p}}^{H1}\text{, dB} \tag{C.5}$$

$$L_{\mathrm{p}}^{n,H2,run} = L_{\mathrm{air}}^{5} + K_{\mathrm{p}}^{H2}\text{, dB} \tag{C.6}$$

Check whether airborne noise interference level is lower than direct measured hydrodynamic noise level 10 dB. If measurement frequency meets this condition, it can be considered that the influence of airborne noise caused by opening pump on the results can be ignored.

If the interference level does not meet this condition, analysing and eliminating the reasons for high noise shall be done, such as using less noise auxiliary equipment or increasing the mass of isolator connecting the pipeline rigidly with the base plate near the test section.

Annex D
(informative)

Formulae for determining passive characteristics of noise source

D.1 Transfer matrix

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{pmatrix} H_{\mathrm{po/pre}}{}^{(1)} & H_{\mathrm{po/pre}}{}^{(2)} \\ H_{\mathrm{qo/pre}}{}^{(1)} & H_{\mathrm{qo/pre}}{}^{(2)} \end{pmatrix} \begin{pmatrix} H_{\mathrm{pi/pre}}{}^{(1)} & H_{\mathrm{pi/pre}}{}^{(2)} \\ H_{\mathrm{qi/pre}}{}^{(1)} & H_{\mathrm{qi/pre}}{}^{(2)} \end{pmatrix}^{-1} \quad \text{(D.1)}$$

where $H_{\mathrm{po/pre}}{}^{(i)}, H_{\mathrm{Qo/pre}}{}^{(i)}, H_{\mathrm{pi/pre}}{}^{(i)}, H_{\mathrm{Qi/pre}}{}^{(i)}, (i=1,2)$ are transfer functions between $P_{\mathrm{o}}, Q_{\mathrm{o}}, P_{\mathrm{i}}, Q_{\mathrm{i}}$ and the reference signal. See Annex A for the definition of $P_{\mathrm{o}}, Q_{\mathrm{o}}, P_{\mathrm{i}}, Q_{\mathrm{i}}$ and the transfer function can be obtained by the hydrophones in Figure 2.

D.2 Impedance matrix

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{pmatrix} H_{\mathrm{po/pre}}{}^{(1)} & H_{\mathrm{po/pre}}{}^{(2)} \\ H_{\mathrm{pi/pre}}{}^{(1)} & H_{\mathrm{pi/pre}}{}^{(2)} \end{pmatrix} \begin{pmatrix} H_{\mathrm{Qo/pre}}{}^{(1)} & H_{\mathrm{Qo/pre}}{}^{(2)} \\ H_{\mathrm{Qi/pre}}{}^{(1)} & H_{\mathrm{Qi/pre}}{}^{(2)} \end{pmatrix}^{-1} \quad \text{(D.2)}$$

The definition of each parameter is the same as the transfer matrix above.

D.3 Scattering matrix

$$\begin{bmatrix} r_{\mathrm{o}} & \tau_{\mathrm{i}} \\ \tau_{\mathrm{o}} & r_{\mathrm{i}} \end{bmatrix} = \begin{pmatrix} H_{\mathrm{po+/pre}}{}^{(1)} & H_{\mathrm{po+/pre}}{}^{(2)} \\ H_{\mathrm{pi+/pre}}{}^{(1)} & H_{\mathrm{pi+/pre}}{}^{(2)} \end{pmatrix} \begin{pmatrix} H_{\mathrm{po-/pre}}{}^{(1)} & H_{\mathrm{po-/pre}}{}^{(2)} \\ H_{\mathrm{pi-/pre}}{}^{(1)} & H_{\mathrm{pi-/pre}}{}^{(2)} \end{pmatrix}^{-1} \quad \text{(D.3)}$$

where $H_{\mathrm{po+/pre}}{}^{(i)}, H_{\mathrm{pi+/pre}}{}^{(i)}, H_{\mathrm{po-/pre}}{}^{(i)}, H_{\mathrm{pi-/pre}}{}^{(i)}, (i=1,2)$ are transfer functions between $p_{\mathrm{o}}^{+}, p_{\mathrm{i}}^{+}, p_{\mathrm{o}}^{-}, p_{\mathrm{i}}^{-}$ and the reference signal. See Annex A for the definition of $p_{\mathrm{o}}^{+}, p_{\mathrm{i}}^{+}, p_{\mathrm{o}}^{-}, p_{\mathrm{i}}^{-}$ and the transfer function can be obtained by the hydrophone in the two test sections.