INTERNATIONAL STANDARD

# ISO 10767-1

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# Hydraulic fluid power — Determination of pressure ripple levels generated in systems and components —

## Part 1:
## Precision method for pumps

*Transmissions hydrauliques — Détermination des niveaux d'onde de pression engendrés dans les circuits et composants —*

*Partie 1: Méthode de précision pour les pompes*



Reference number
ISO 10767-1:1996(E)

## Contents







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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.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 10767-1 was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 8, *Product testing and contamination control*.

ISO 10767 consists of the following parts, under the general title *Hydraulic fluid power — Determination of pressure ripple levels generated in systems and components*:

— *Part 1: Precision method for pumps*

— *Part 2: Simplified method for pumps*

— *Part 3: Method for motors*

Annexes A and B form an integral part of this part of ISO 10767. Annexes C and D are for information only.

## Introduction

In hydraulic fluid power systems, power is transmitted and controlled through a liquid under pressure within an enclosed circuit. Positive-displacement 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 system at levels depending upon the characteristics of the pump and the circuit. Thus, the determination of the pressure ripple generated by a pump is complicated by the interaction between the pump and the circuit. The method adopted to measure the pressure ripple levels of a pump should, therefore, be such as to eliminate this interaction.

The measurement technique described in this part of ISO 10767 isolates the pump flow and/or pressure ripple from the effects of such circuit interactions, by mathematical processing of pressure ripple measurements (see refs. [1] to [8]). A figure of merit for the pump is obtained which allows pumps of different types and manufacture to be compared as pressure ripple generators. This will enable the pump designer to evaluate the effect of design modifications on the pressure ripple levels produced by the pump in service. It will also enable the hydraulic system designer to avoid selecting pumps having high pressure ripple levels.

The method is based upon the application of plane wave transmission line theory to the analysis of pressure fluctuations in hydraulic systems [9]. By evaluating the impedance characteristics of the circuit into which the pump discharges and the impedance of the pump itself, it is possible to isolate the source flow ripple and/or pressure ripple of the pump from the interactions of the circuit. The impedance characteristics of the circuit can be evaluated by analysis of pressure ripple measurements at two or more positions along a pipe, where the pipe is connected to the discharge port of the pump. However, to characterize the impedance of the system completely, it is not sufficient to measure the pressure ripple generated by the pump alone, as insufficient information is available for the impedance of the pump to be evaluated. The secondary-source method uses another source of pressure ripple at the opposite end of the discharge line. The measurement of this pressure ripple enables the pump source impedance to be evaluated. Sufficient information is then available to evaluate the source flow ripple and pressure ripple of the pump.

Because of the complexity of the analysis, data processing is preferably carried out using a digital computer. Suitable software packages are available from two sources (see annex C).

# Hydraulic fluid power — Determination of pressure ripple levels generated in systems and components —

## Part 1: Precision method for pumps



## 1 Scope

This part of ISO 10767 specifies a procedure for the determination of a rating of the source flow ripple, source impedance and pressure ripple levels generated by positive-displacement hydraulic pumps. Ratings are obtained as the following:

a) the source flow ripple amplitude, in litres per second, over ten individual harmonics of pumping frequency;

b) the source impedance amplitude, in newton seconds per metre to the power of five [(N·s)/m$^5$], and phase, in degrees, over ten individual harmonics of pumping frequency;

c) the anechoic pressure ripple amplitude, in bars[1)], over ten harmonics of pumping frequency;

d) the overall r.m.s. anechoic pressure ripple, in bars;

e) the blocked acoustic pressure ripple amplitude, in bars, over ten harmonics of pumping frequency;

f) the overall r.m.s. blocked acoustic pressure ripple, in bars.

This part of ISO 10767 is applicable to all types of positive-displacement pump operating under steady-state conditions, irrespective of size, provided that the pumping frequency is in the range from 50 Hz to 400 Hz.

1) 1 bar = $10^5$ Pa = $10^5$ N/m$^2$

## 2 Definitions

For the purposes of this part of ISO 10767, the following definitions apply.

**2.1 source flow ripple:** Fluctuating component of flowrate generated within the pump, which is independent of the characteristics of the connected circuit.

**2.2 flow ripple:** Fluctuating component of flowrate in the hydraulic fluid, caused by interaction of the source flow ripple with the system.

**2.3 pressure ripple:** Fluctuating component of pressure in the hydraulic fluid, caused by interaction of the source flow ripple with the system.

**2.4 anechoic pressure ripple:** Pressure ripple that would be generated at the pump discharge port when discharging into an infinitely long rigid pipe of the same internal diameter as the pump discharge port.

**2.5 blocked acoustic pressure ripple:** Pressure ripple that would be generated at the pump discharge port when discharging into a circuit of infinite impedance.

**2.6 impedance:** Complex ratio of the pressure ripple to the flow ripple occurring at a given point in a hydraulic system and at a given frequency.

**2.7 source impedance:** Impedance of a pump at the discharge port.

**2.8 harmonic:** Sinusoidal component of the pressure ripple or flow ripple occurring at an integral multiple of the pumping frequency.

NOTE 1 A harmonic may be represented by its amplitude and phase, or alternatively by its real and imaginary components.

**2.9 pumping frequency:** Frequency given by the product of shaft rotational frequency and the number of pumping elements on that shaft. It is expressed in hertz.

**2.10 shaft rotational frequency:** Frequency (in hertz) given by the shaft rotational speed (in r/min) divided by 60.

# 3 Instrumentation

## 3.1 Static measurements

The instruments used to measure

a) mean fluid flow,

b) mean fluid pressure,

c) shaft rotational speed, and

d) fluid temperature

shall meet the temperature for "industrial class" accuracy of measurement, i.e. class C given in annex A.

## 3.2 Dynamic measurements

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

a) resonant frequency $\geqslant$ 30 kHz;

b) linearity $< \pm 1$ %.

The instruments need not respond to steady-state pressure, and it may be advantageous to filter out any steady-state signal component using a high-pass filter. This filter shall not introduce an additional amplitude or phase error exceeding 1 % or 2°, respectively, at the pumping frequency.

## 3.3 Frequency analysis of pressure ripple

A suitable instrument shall be used to measure the amplitude and phase of the pressure ripple, for at least ten harmonics of the pumping frequency.

The instrument shall be capable of measuring the pressure ripple from two or three pressure transducers (6.7) such that, for a particular harmonic, the measurements from each transducer are synchronized in time with respect to each other. This may be achieved by sampling the pressure ripple from each pressure transducer simultaneously, or by sampling each pressure transducer separately but with respect to a trigger signal obtained from a fixed reference on the pump shaft or secondary source drive, as appropriate.

The instruments shall have an accuracy and resolution for harmonic measurements as follows, over the frequency range from 50 Hz to 4 000 Hz:

a) amplitude within $\pm$ 1 %;

b) phase within $\pm$ 1°;

c) frequency within $\pm$ 0,5 %.

Compliance with the above tolerances will result in an uncertainty in the overall r.m.s. pressure ripple rating of within $\pm$ 10 %.

# 4 Pump installation

## 4.1 General

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

## 4.2 Drive vibration

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.

## 4.3 Reference signal

A means of producing a reference signal relative to the pump shaft rotation shall be included. The signal shall be an electrical pulse occurring once per revolution, with sharply defined rising and falling edges. This signal is used as a measure of the shaft rotational speed and may be used, if necessary, to provide a trigger signal and/or phase reference for the pressure ripple analysis instrument.

## 5 Test conditions

### 5.1 General

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

### 5.2 Fluid temperature

The temperature of the fluid shall be that measured at the pump inlet.

### 5.3 Fluid density and viscosity

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

### 5.4 Fluid bulk modulus

The isentropic tangent bulk modulus of the fluid shall be known to an accuracy within the limits specified in table 2. As this is not always feasible, B.4.2 details a method by which the bulk modulus may be evaluated with a sufficiently high accuracy.

**Table 1 — Permissible variations in test conditions**

| Test parameter | Permissible variation |
|---|---|
| Mean flow | ± 2 % |
| Mean pressure | ± 2 % |
| Shaft rotational frequency | ± 1 % |
| Temperature | ± 2 °C |

**Table 2 — Required accuracy of fluid property data**

| Property | Required accuracy |
|---|---|
| Density1) | ± 2 % |
| Viscosity1) | ± 5 % |
| Isentropic tangent bulk modulus2) | ± 5 % |

1) See reference [10].

2) See reference [11].

## 6 Test rig

### 6.1 General

The test rig shall be installed generally as shown in figure 1. The test rig shall include all fluid filters, fluid coolers, reservoirs, loading valves and any ancillary pumps required to meet the pump hydraulic operating conditions. Specific features are described in 6.2 to 6.13.

### 6.2 Test fluid

The type of test hydraulic fluid and the quality of filtration shall be in accordance with the pump manufacturer's recommendations.

### 6.3 Pump

The pump shall be installed in the "as-delivered" condition.

### 6.4 Inlet line

The internal diameter of the inlet line to the pump shall be in accordance with the pump manufacturer's recommendations. To prevent air leaking into the circuit, care shall be exercised when assembling the inlet lines. The supply pressure shall be in accordance with the pump manufacturer's recommendations and, if necessary, a boost pump shall be used.

### 6.5 Inlet pressure gauge

The inlet pressure gauge shall be mounted at the same height as the inlet fitting or shall be calibrated for any height difference therefrom.

### 6.6 Pump discharge port connection

The adaptor connecting the pump discharge port to the discharge pipe shall have an internal diameter which does not differ from the discharge 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 discharge pipe shall be mounted in line with the pump discharge port without any changes in direction.

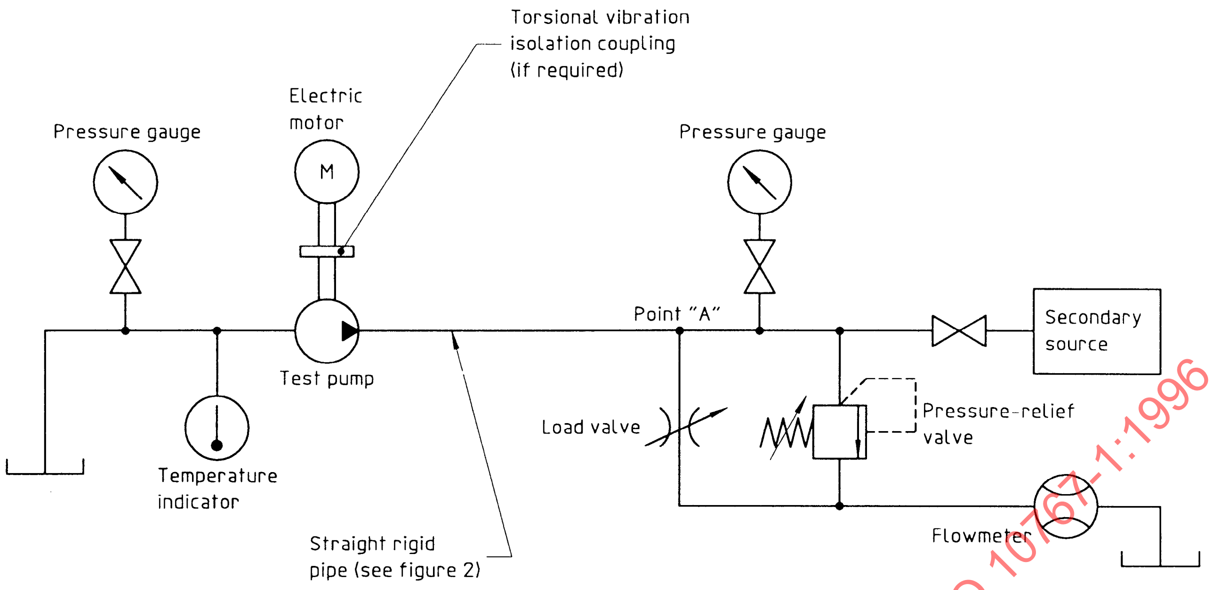



**Figure 1 — Circuit diagram for secondary-source test rig**



## 6.7 Pump discharge line

The discharge pipe shall be a uniform, rigid, straight metal pipe. Pressure transducers shall be mounted along its length, as shown in figure 2. The internal diameter of the pipe shall be between 80 % and 120 % of the diameter of the pump discharge port. The pipe shall be supported in such a manner that pipe vibration is minimized.

The pressure transducers shall be mounted such that their diaphragms are flush with the inner wall of the pipe to within ± 0,5 mm. No valves, pressure gauges or flexible hoses shall be installed between the pump discharge port and point "A" as shown on figure 1.

Two alternative specifications for the pump discharge line are given, depending on whether the isentropic tangent bulk modulus of the fluid is known within the limits specified in table 2. These alternatives are henceforth known as "method 1" and "method 2". Method 1 is acceptable for use in all situations. However, if the isentropic tangent bulk modulus is known within the limits specified in table 2, economies can be made by using method 2.

If method 1 is used, set up the pump discharge line as specified in 6.7.1. If method 2 is used, set it up as specified in 6.7.2.

### 6.7.1 Method 1

Three pressure transducers are required for this method, set up as shown in figure 2. The dimensions of the discharge pipe shall be selected according to the pumping frequency. When the series of tests includes a range of pump speeds, the dimensions shall be selected in relation to the minimum pumping frequency, $f_{0,min}$, in that series. The overall length of the discharge pipe, $l$, and the distance of the pressure transducers from the pump, $x_1$, $x_2$ and $x_3$, are specified in table 3.

**Table 3 — Pipe length and transducer positions: Method 1**

| Pipe length and transducer positions | Minimum pumping frequency, Hz | |
|---|---|---|
| | $50 \leqslant f_{0,min} \leqslant 100$ | $100 < f_{0,min} \leqslant 400$ |
| $x_1$ | 0,15 m ± 1 % | 0,1 m ± 1 % |
| $x_2$ | 0,85 m ± 1 % | 0,43 m ± 1 % |
| $x_3$ | 1,85 m ± 1 % | 0,9 m ± 1 % |
| $l$ | at least 2 m | at least 1 m |

### 6.7.2 Method 2

Two pressure transducers are required for this method, set up as shown in figure 2. The length of the discharge pipe and the positions of the pressure transducers shall be selected according to the pumping frequency. When the series of tests includes a range of pumping frequencies, the dimensions shall be selected in relation to the maximum pumping frequency in that series. The ratio of maximum to minimum speed for a selected transducer spacing shall not exceed 4:1. If the speed range of a test series exceeds this limit, different transducer spacings will be required.

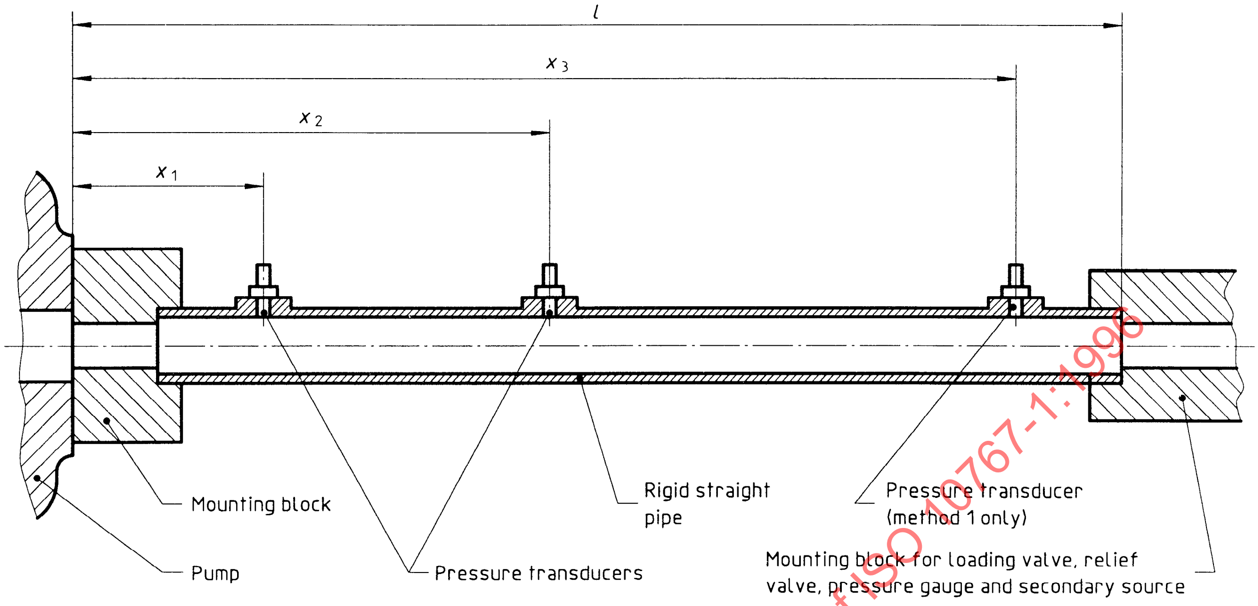



**Figure 2 — Arrangement of discharge pipe**



The distance between the pressure transducers shall be as given by the following equation, to within 1 %:

$$x_2 - x_1 = \frac{\sqrt{\left(B_{\text{eff}} \times 10^5/\varrho\right)}}{(67 \times f_{0,\,\max})}$$

where

$f_{0,\,\max}$ is the maximum pumping frequency, in hertz;

$B_{\text{eff}}$ is the effective bulk modulus, in bars (see B.3);

$\varrho$ is the density, in kilograms per cubic metre.

The first pressure transducer shall be located as close as possible to the pump flange and no more than $(x_2 - x_1)$ m away. The length $l$ shall be at least $(x_2 + 10d)$ m, where $d$ is the internal diameter of the pipe.

#### 6.7.3 Calibration of pressure transducers

Calibration of the pressure transducers and signal conditioning is necessary. Relative calibration shall be performed by mounting the pressure transducers in a common block such that they measure the same pressure ripple. This common block shall be such that the pressure transducers are at the same axial position and not more than 20 mm apart.

Use the secondary source (6.11) to generate pressure ripple. Measure the amplitude and phase relationship between the pressure transducers for a range of frequencies spanning the complete range of interest (7.3.2) with one transducer used as a reference. For piezo-resistive transducers, the reference transducer can be calibrated statically using, for example, a dead-weight testing machine. If piezo-electric transducers and charge amplifiers are employed, a calibrated piezo-resistive transducer may be used as a reference for dynamic calibration purposes. The amplitude and phase differences at each frequency shall be known to an accuracy of within 3 % and 2° for method 1, or 3 % and 0,5° for method 2. These differences shall be corrected in the tests (see clause 7).

### 6.8 Load valve

Loading of the pump shall be effected using a needle valve or equivalent. A valve with freely moving parts, such as a pressure-relief valve, shall not be used for loading purposes.

### 6.9 Relief valve

A relief valve may be fitted for safety purposes. The valve shall be set to relieve at a pressure at least 20 % greater than the mean test pressure.

### 6.10 Pressure gauge

A pressure gauge shall be fitted as shown in figure 1, together with a throttling valve to reduce gauge oscillation. Alternatively, a pressure transducer may be used.

### 6.11 Secondary source

**6.11.1** A device capable of generating pressure ripple shall be fitted as shown in figure 1.

**6.11.2** The pressure ripple from the secondary source shall span the frequency range from the pumping frequency of the test pump to at least ten times the pumping frequency.

**6.11.3** The pressure ripple from the secondary source shall have a periodic waveform. The secondary source may produce either a multi-harmonic pressure ripple waveform or a pressure ripple waveform which may be swept in discrete frequency steps to cover the range specified in 6.11.2. Pressure ripple shall be measurable at a minimum of ten frequencies over this range. The harmonic frequencies from the secondary source shall not vary by more than 0,5 % once a stable running condition has been achieved.

**6.11.4** It is necessary that the frequencies of the components of the pressure ripple from the secondary source be different from those of the test pump, in order that they may be measured without interference.

**6.11.5** Devices which are suitable for the secondary source include the following.

a) **Positive-displacement pump**: a piston pump is likely to provide strong harmonic components over a broader frequency range than, for example, a gear pump, and is thus likely to be more suitable.

b) **Intermittent bleed-off**, such as valve with a rotating spool allowing flow to pass to the return line over part of its rotation.

c) **Electromechanical vibrator and piston arrangement**.

### 6.12 Ball valve

A ball valve shall be used to isolate the secondary source from the high-pressure part of the circuit. This valve shall be sufficiently large to present negligible restriction to flow when open, in order to prevent excessive attenuation of the pressure ripple from the secondary source.

### 6.13 Mounting

The discharge pipe, valves and secondary source shall be mounted such as to prevent excessive vibration, and shall be adequately supported.

## 7 Test procedure

### 7.1 General

The test procedure involves two separate parts: evaluation of the source impedance and of the source flow ripple. The source flow ripple cannot be evaluated without first evaluating the source impedance. Data acquisition and data reduction are normally performed separately.

Prior to the commencement of a series of tests, operate the pump for a sufficient period of time to purge air from the system and to stabilize all variables, including the condition of the fluid, to within the limits given in table 1.

### 7.2 Test series

For each test, repeat the procedure described in 7.3 to 7.5.

The test is invalid if the peak-to-peak value of the pressure ripple at any one pressure transducer is greater than 50 % of the value of the mean pressure. [If necessary, it may be possible to avoid this condition by altering the pipe length $l$ (6.7).]

### 7.3 Evaluation of source impedance

In this part of the test the pressure ripple from the secondary source is considered. It is essential that this be measured in isolation from the pressure ripple produced by the test pump. This may be achieved by satisfying each of the following criteria.

a) The pressure ripple shall be measured only at harmonic frequencies of the secondary source. If a trigger signal is required by the instrument, this is also taken from the secondary source.

b) The pressure ripple analysis instrument shall sample the pressure ripple signals over a sufficiently long period of time to provide the required frequency resolution.

c) The harmonic frequencies of the secondary source shall not coincide with those of the pump (6.11).

**7.3.1** Open the ball valve (6.12). Operate the secondary source for a sufficient period of time for it to reach a stable condition before taking any measurement.

**7.3.2** Measure at least ten frequency components from the pressure transducers, sufficient to span the frequency range from the pumping frequency of the test pump to beyond ten times that pumping frequency.

**7.3.3** If method 1 is used (6.7.1), analyse the pressure ripple using the procedure described in B.4.

**7.3.4** If method 2 is used (6.7.2), analyse the pressure ripple using the procedure described in B.5.

**7.3.5** Select whether a distributed-parameter or lumped-parameter mathematical model is to be used, as described in B.6. Apply a mathematical model to the source impedance using the procedure described in B.6.1 for a distributed-parameter model, or B.6.2 for a lumped-parameter model.

**7.3.6** In certain circumstances it may be possible to obtain good correlation between the experimentally measured source impedance and the mathematical model. Should this be the case, the curve-fitting technique is inappropriate. It is then necessary to evaluate the source impedance at the harmonic frequencies of the pump by linear interpolation. In order to perform this, the source impedance at a pump harmonic frequency shall be evaluated by interpolating between the measured source impedance at the nearest frequency above and below the pump harmonic frequency, providing that these frequencies comply with the following:

$$(f_i - f_0/10) < f_L < f_i$$

$$f_i < f_H < (f_i + f_0/10)$$

where

$f_i$ is the frequency of the $i$th harmonic from the test pump;

$f_0$ is the fundamental frequency of the test pump;

$f_L$ is the nearest harmonic frequency from the secondary source above the $i$th harmonic frequency from the test pump;

$f_H$ is the nearest harmonic frequency from the secondary source above the $i$th harmonic frequency from the test pump.

It should be noted that a variable-speed secondary source will normally be necessary to comply with the above requirements.

## 7.4 Evaluation of source flow ripple, anechoic pressure ripple and blocked acoustic pressure ripple

Stop the secondary source and close the ball valve. If a trigger signal is required by the pressure ripple analysis instrument, this shall be from the shaft of the test pump (4.3).

At each pressure transducer, measure ten harmonics of the pressure ripple from the test pump.

### 7.4.1 Method 1

If method 1 is used (6.7.1), evaluate the speed of sound using the procedure described in B.4.2. Evaluate the harmonic amplitudes of the source flow ripple using the procedure described in B.7.1.

### 7.4.2 Method 2

If method 2 is used (6.7.2), evaluate the harmonic amplitudes of the source flow ripple using the procedure described in B.7.2.

NOTE 2 A close approximation to the waveform of the source flow ripple can be obtained by summing the individual sinusoidal components taking their relative phases into account. It is sometimes desirable to be able to reconstruct the waveform of the source flow ripple in this way. In order to do this, the values of the phase of the source flow ripple are required in addition to the amplitude. If a distributed-parameter source impedance model was used in the analysis, more representative results will be obtained by referring the measured source flow ripple from the pump discharge port to a point within the pump. A procedure for performing this is described in reference [2]. This is not necessary to comply with this part of ISO 10767.

## 7.5 Calculation of anechoic pressure ripple rating

Evaluate the harmonic amplitudes of the anechoic pressure ripple using the procedure described in B.8.

Use the harmonic components of the anechoic pressure ripple to provide the overall anechoic pressure ripple rating for the pump. Determine the overall anechoic pressure ripple rating, in bars, from the expression

$$\sqrt{\left(P_{a,1}^2 + P_{a,2}^2 + P_{a,3}^2 + \dots + P_{a,10}^2\right)/2}$$

where $P_{a,1}$, $P_{a,2}$, $P_{a,3}$, etc. are the amplitudes of the anechoic pressure ripple, in bars, at the corresponding harmonic number.

### 7.6 Calculation of blocked acoustic pressure ripple rating

Evaluate the harmonic amplitudes of the blocked acoustic pressure ripple using the procedure described in B.9.

Use the harmonic components of the blocked acoustic pressure ripple to provide the overall blocked acoustic pressure ripple rating for the pump. Determine the overall blocked acoustic pressure ripple rating, in bars, from the expression

$$\sqrt{\left(P_{b,1}^2 + P_{b,2}^2 + P_{b,3}^2 + \dots + P_{b,10}^2\right)/2}$$

where $P_{b,1}$, $P_{b,2}$, $P_{b,3}$, etc. are the amplitudes of the blocked acoustic pressure ripple, in bars, at the corresponding harmonic number.

### 7.7 Use of new or rebuilt pump

Repeat the initial pump measurement of the series at the end of a test series or after 1 h of testing.

The whole test series shall be deemed to be invalid if the overall anechoic pressure ripple rating does not duplicate that of the first test within ± 10 %.

## 8 Test report

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

### 8.1 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 (see clause 9).

### 8.2 Test data

a) Description of pump:

1) type of pump (e.g. external gear, axial piston) including any ancillary equipment;

2) type of displacement (e.g. fixed or variable);

3) pump maximum displacement;

4) type of displacement controller and setting;

5) number of pumping elements;

6) diameter of discharge port, in millimetres.

b) Mounting and installation conditions of pump:

1) description of pump mounting conditions;

2) nature and characteristics of the hydraulic circuit and details of any vibration isolation treatment;

3) type and power of pump drive.

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 for pressure ripple measurements including type, serial number and manufacturer;

4) bandwidth of frequency analyser;

5) overall frequency response of instrumentation system and date and method of calibration;

6) method of calibration of pressure transducers and date and place of calibration.

d) Test method adopted (method 1 or method 2).

e) Description of secondary source: type of unit (e.g. axial piston pump, electromechanical vibrator).

f) Pump operating conditions; include the following details for each test conducted:

1) type of fluid;

2) kinematic viscosity, in centistokes (cSt)[2];

3) fluid density, in kilograms per cubic metre;

4) effective isentropic tangent bulk modulus, in bars;

5) shaft rotational speed, in revolutions per minute;

6) mean inlet pressure, in bars;

7) mean outlet pressure, in bars;

8) mean pump delivery flow, in litres per minute;

9) temperature of fluid at pump inlet, in degrees Celsius.

### 8.3 Test results

a) Amplitude of the anechoic pressure ripple components, in bars, for ten harmonics of pumping frequency.

b) Overall anechoic pressure ripple rating, in bars.

c) Amplitude of the blocked acoustic pressure ripple components, in bars, for ten harmonics of pumping frequency.

d) Overall blocked acoustic pressure ripple rating, in bars.

e) Amplitude of the source flow ripple components (in litres per second) for ten harmonics of pumping frequency.

f) Amplitude [in $(N{\cdot}s)/m^5$] and phase (in degrees) of the source impedance components for ten harmonics of pumping frequency.

g) Type of source impedance model used (lumped- or distributed-parameter model), or linear interpolation.

## 9 Identification statement (Reference to this part of ISO 10767)

Use the following statement in test reports, catalogues and sales literature when electing to comply with this part of ISO 10767:

"Pressure and flow ripple levels in accordance with ISO 10767-1:1996, *Hydraulic fluid power — Determination of pressure ripple levels generated in systems and components — Part 1: Precision method for pumps.*"



2) 1 cSt = 1 $mm^2/s$.

# Annex A
(normative)

# Errors and classes of measurement

## A.1 Classes of measurement

Depending on the accuracy required, carry out the tests to one of three classes of measurement, A, B or C. Although the procedures described assume that measurements are made to class C, in special cases when there is need to have the performance more precisely defined, use class A or B by agreement with the parties concerned. Attention is drawn to the fact that class A and B measurements require more accurate apparatus and methods, which increase the cost of such tests.

## A.2 Errors

Use any device or method that by calibration or comparison with International Standards has been demonstrated to be capable of measuring with systematic errors not exceeding the limits given in table A.1.



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

| Class of measurement | Shaft rotational frequency<br>% | Mean flow<br>% | Mean pressure<br>% | Temperature<br>°C |
|---|---|---|---|---|
| A | ± 0,2 | ± 0,5 | ± 0,5 | ± 0,5 |
| B | ± 0,5 | ± 1,5 | ± 1,5 | ± 1 |
| C | ± 1 | ± 2,5 | ± 2,5 | ± 2 |

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

# Annex B
(normative)

# Data reduction algorithms

## B.1 General

The experimentally measured harmonic pressure ripple data need to be mathematically processed in order to evaluate the source flow ripple of the pump. Because of the complexity of the analysis, data processing is preferably carried out using a digital computer.

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

## B.2 Explanation of notation

Extensive use of complex numbers is made in this analysis. The following notation applies, in which the complex number $x$ is represented by its real and imaginary components $(a + jb)$, where $j = \sqrt{-1}$ and $a$ and $b$ are real numbers.

a) $\bar{x}$ denotes the complex conjugate of $x$, i.e. $\bar{x} = (a - jb)$

b) $|x|$ denotes the amplitude of $x$, i.e. $|x| = \sqrt{(a^2 + b^2)}$

c) $\angle x$ denotes the phase of $x$ (in degrees), i.e. $\angle x = (180/\pi) \times \tan^{-1}(b/a)$. Care should be taken to ensure that the phase of $x$ lies in the correct quadrant.

d) $\mathrm{Re}(x)$ denotes the real part of $x$, i.e. $\mathrm{Re}(x) = a$

e) $\mathrm{Im}(x)$ denotes the imaginary part of $x$, i.e. $\mathrm{Im}(x) = b$

$P_{m,i}$ is a complex value representing the $i$th harmonic of pressure ripple at location $m$. Pressure ripple measurements are assumed to be peak values as opposed to r.m.s. values. To convert r.m.s. values to peak values, multiply the amplitude of pressure ripple harmonics by $\sqrt{2}$.

## B.3 Data related to pump test

The following data are required regarding the pump, the pump operating conditions and the test fluid, within the limits specified here or in table 1 or 2.

a) **Pump**:

1) diameter of the pump discharge port, $d_p$, in millimetres;

2) number of pumping elements, $r$.

b) **Pump operating conditions**:

1) mean test pressure, $p$, in bars;

2) mean flowrate, $q$, in litres per second;

3) temperature of test fluid, $\theta$, in degrees Celsius;

4) shaft rotational speed, $N$, in revolutions per minute.

c) **Test fluid and discharge pipe**:

1) estimated isentropic tangent bulk modulus, $B$, in bars, of test fluid at pressure $p$ and temperature $\theta$ (see 6.7);

2) mass density, $\varrho$, in kilograms per cubic metre, of test fluid at pressure $p$ and temperature $\theta$;

3) kinematic viscosity, $\nu$, in centistokes, of test fluid at pressure $p$ and temperature $\theta$;

4) internal diameter of discharge pipe, $d$, in millimetres $\pm$ 0,1 mm;

5) thickness of pipe wall, $t$, in millimetres $\pm$ 0,1 mm;

6) Young's modulus of pipe wall, $E$, in newtons per square metre $\pm$ 10 %;

7) distance $x_i$, in metres $\pm$ 1 mm, of pressure transducer $m$ from pump discharge port for $m = 1$ to 3.

Calculate the effective bulk modulus, taking the stiffness of the pipe wall into account, using the equation

$$B_{\text{eff}} = \frac{B}{1 + \left[(d+t)B \times 10^5\right]/(tE)} \qquad \text{. . . (B.1)}$$

## B.4 Evaluation of source impedance using method 1

### B.4.1 Theoretical pressure ripple and flow ripple behaviour in a rigid pipe

Under the operating conditions generally encountered in hydraulic systems, the pressure and flow ripple in a pipe can be described using a one-dimensional formulation of the wave equations [6]. At a frequency $f$ Hz, the harmonic values of the pressure ripple and the flow ripple at a point $x$ (in metres) along the pipe are given by:

$$P = F\text{e}^{-\gamma x} + G\text{e}^{\gamma x} \qquad \text{. . . (B.2)}$$

$$Q = (F\text{e}^{-\gamma x} - G\text{e}^{\gamma x})/Z_0 \qquad \text{. . . (B.3)}$$

where

$F$ and $G$ are dependent upon the boundary conditions;

$\gamma$ is the complex wave propagation coefficient, in reciprocal metres, given by

$$\gamma = j2\pi f\xi/c_0 \qquad \text{. . . (B.4)}$$

$Z_0$ is the complex characteristic impedance of the pipe [in (N·s)/m$^5$], given by

$$Z_0 = 4\varrho c_0 \xi / \left(\pi d^2 \times 10^{-6}\right) \qquad \text{. . . (B.5)}$$

$c_0$ is the speed of sound given by

$$c_0 = \sqrt{\left(B_{\text{eff}} \times 10^5\right)/\varrho} \qquad \text{. . . (B.6)}$$

$\xi$ is a complex number representing viscous effects in the pipe and is defined by

$$\xi = \sqrt{K_1 + \left(8jK_2/N_s^2\right)} \qquad \text{. . . (B.7)}$$

$K_1$ and $K_2$ are functions of $N_s$, the wave shear number, which is given by

$$N_s = 0{,}5d\sqrt{2\pi f/\nu} \qquad \text{... (B.8)}$$

For $N_s \geqslant 8$, the values of $K_1$ and $K_2$ are approximated to

$$K_1 = 1 + (\sqrt{2}/N_s) \qquad \text{... (B.9)}$$

$$K_2 = 0{,}425 + 0{,}175N_s \qquad \text{... (B.10)}$$

For $N_s < 8$, the following approximations are used:

$$K_1 = 1{,}333 - 4{,}66 \times 10^{-3}N_s^2 + 2{,}73 \times 10^{-4}N_s^3 \qquad \text{... (B.11)}$$

$$K_2 = 1{,}0 + 0{,}0203N_s^2 - 7{,}81 \times 10^{-4}N_s^3 \qquad \text{... (B.12)}$$

### B.4.2 Evaluation of speed of sound in the fluid

The accuracy of the results obtained using the secondary-source method is dependent on the accuracy to which the speed of sound, $c_0$, is known. The speed of sound is a function of the effective isentropic tangent bulk modulus of the fluid, $B_{eff}$, which may be difficult to predict accurately and may be affected by the entrained air in the fluid.

Method 1 incorporates a technique for the experimental evaluation of the speed of sound, from which the effective bulk modulus may be inferred.

An iterative method is employed for the calculation of $c_0$ and $B_{eff}$. This method requires a starting value for $c_0$ based on an estimate of the effective bulk modulus $B'_{eff}$. This is obtained from the equation

$$c_{0,OLD} = \sqrt{\left(B'_{eff} \times 10^5\right)/\varrho} \qquad \text{... (B.13)}$$

Iteration proceeds by calculating a correction to $c_0$, i.e.

$$c_{0,NEW} = c_{0,OLD} + \beta \Delta c_0 \qquad \text{... (B.14)}$$

where, for $n$ harmonics

$$\Delta c_0 = \frac{\sum_{i=1}^{n} \mathrm{Re}(\varepsilon_i \bar{\zeta}_i)}{\sum_{i=1}^{n} \zeta_i \bar{\zeta}_i} \qquad \text{... (B.15)}$$

$$\varepsilon_i = P_{1,i} \sin[k(x_3 - x_2)] + P_{2,i} \sin[k(x_1 - x_3)] + P_{3,i} \sin[k(x_2 - x_1)] \qquad \text{... (B.16)}$$

$$\zeta_i = k/c_{0,OLD}\{P_{1,i}(x_3 - x_2) \cos[k(x_3 - x_2)] + P_{2,i}(x_1 - x_3) \cos[k(x_1 - x_3)] + P_{3,i}(x_2 - x_1) \cos[k(x_2 - x_1)]\} \qquad \text{... (B.17)}$$

where $P_{m,i}$ is the $i$th harmonic of the pressure ripple measured at the $m$th transducer position, and

$$k = 2\pi f_i \sqrt{K_1}/c_{0,OLD} \qquad \text{... (B.18)}$$

$K_1$ is defined by equations (B.8), (B.9) and (B.11).

$\beta$ is a relaxation factor and provides some control over the speed and stability of the iteration without affecting the converged solution. Normally $0 < \beta \leqslant 1$. A small value of $\beta$ may aid convergence, but can slow down the iteration process. Typically $\beta = 0{,}7$.

Continue iteration using equations (B.14) to (B.18) until the magnitude of $\Delta c_0$ is less than $c_{0,OLD} \times 10^{-4}$.

This iteration process has the effect of minimizing the "sum of squared errors" (see reference [9]):

$$\text{sum of squared errors} = \sum_{i=1}^{n} |\zeta_i|^2 \qquad \text{... (B.19)}$$

Upon completion of the iteration, calculate the effective bulk modulus (in bars), using the equation

$$B_{\text{eff}} = \varrho c_0^2 \times 10^{-5} \qquad \text{... (B.20)}$$

### B.4.3 Evaluation of source impedance

For each measured secondary-source harmonic $i$, evaluate the source impedance $Z_{S,i}$ by solution of the equations

$$Z_{S,i} = Z_0 \frac{t_2 s_{1,1} - t_1 s_{2,1} + t_1 s_{2,2} - t_2 s_{1,2}}{t_2 s_{1,1} - t_1 s_{2,1} - t_1 s_{2,2} + t_2 s_{1,2}} \qquad \text{... (B.21)}$$

where, for three pressure transducers:

$$s_{k,l} = \sum_{m=1}^{3} \left[ \overline{f_k(x_m)}\, f_l(x_m) \right] \qquad \text{... (B.22)}$$

$$t_k = \sum_{m=1}^{3} \left[ P_{m,i}\, \overline{f_k(x_m)} \right] \qquad \text{... (B.23)}$$

and

$$f_1(x) = e^{-\gamma x} \qquad \text{... (B.24)}$$

$$f_2(x) = e^{\gamma x} \qquad \text{... (B.25)}$$

The values of $\gamma$ and $Z_0$ at each harmonic are evaluated using equations (B.4) to (B.12).

## B.5 Evaluation of source impedance using method 2

For each harmonic $i$ of the pressure ripple from the secondary source, calculate the spatial average pressure ripple $P_{A,i}$ (in bars) and average flow ripple $Q_{A,i}$ (in litres per second) at the mean position between the two transducers according to the equations

$$P_{A,i} = (P_{1,i} + P_{2,i})/2 \qquad \text{... (B.26)}$$

$$Q_{A,i} = \frac{A}{j2\pi f_i \varrho} \times \frac{(P_{1,i} - P_{2,i}) \times 10^8}{(x_2 - x_1)} \qquad \text{... (B.27)}$$

where

$f_i$ is the harmonic frequency, in hertz;

$A$ is the pipe internal cross-sectional area, in square metres, given by

$$A = \pi d^2 \times 10^{-6}/4 \qquad \text{... (B.28)}$$

$P_{m,i}$ is the $i$th harmonic of the pressure ripple measured at the $m$th transducer position.

Calculate the source impedance [in (N·s)/m$^5$] using the equation

$$Z_{S,i} = -Z_0 \left[ \frac{P_{A,i} \cos(kx_A) + jZ_0 Q_{A,i} \times 10^{-8} \sin(kx_A)}{Z_0 Q_{A,i} \times 10^{-8} \cos(kx_A) + jP_{A,i} \sin(kx_A)} \right] \qquad \text{... (B.29)}$$

where

$$k = 2\pi f_i \sqrt{\varrho l \left(B_{eff} \times 10^5\right)} \qquad \text{... (B.30)}$$

$$Z_0 = \frac{\sqrt{\varrho B_{eff}}}{A} \qquad \text{... (B.31)}$$

$$x_A = (x_1 + x_2)/2 \qquad \text{... (B.32)}$$

## B.6 Modelling of source impedance

For each harmonic $i$, evaluate the amplitude $|Z_{S,i}|$ and phase $\angle Z_{S,i}$ of the source impedance.

The values of source impedance evaluated using the above methods are at frequencies which are different from the frequencies of the harmonics of the test pump. In order to evaluate the source impedance at the harmonic frequencies of the test pump, a curve-fitting technique is applied to the experimental data.

The source impedance of positive-displacement pumps can generally be approximated by a mathematical equation representing a simplification of the physical characteristics of the discharge passageway [10].

A mathematical function, based upon the known characteristics of the pump discharge passageway, is applied to the experimentally evaluated source impedance in order to minimize the sum of squares error between the two. This mathematical function is a representation of either

a) a uniform, closed-ended length of pipe (distributed parameter), or

b) a simple volume of compressible fluid (lumped parameter).

The selection of the model used depends upon the range of frequencies of interest. In order to select which model is employed, it is necessary to plot graphs of the amplitude [in (N·s)/m$^5$ on a logarithmic scale] and phase (in degrees on a linear scale) of the source impedance against frequency (on a logarithmic scale).

The form of the source impedance should resemble either figure B.1 or B.2. If the source impedance clearly exhibits an anti-resonance, as is shown in figure B.1, at which the amplitude reaches a minimum and the phase changes from negative to positive, then model 1 shall be used. If no such anti-resonance is apparent and the phase remains negative, as shown in figure B.2, then model 2 shall be used. Note that any isolated spurious experimental points should be ignored in the above inspection.

NOTE 3 In addition to an anti-resonance, a resonance at which the amplitude reaches a maximum and the phase changes from positive to negative may be apparent at a higher frequency than the anti-resonance. Model 1 is appropriate for this case.

If the measured source impedance does not resemble figure B.1 or B.2, then an interpolation method shall be used, as described in 7.3.6.

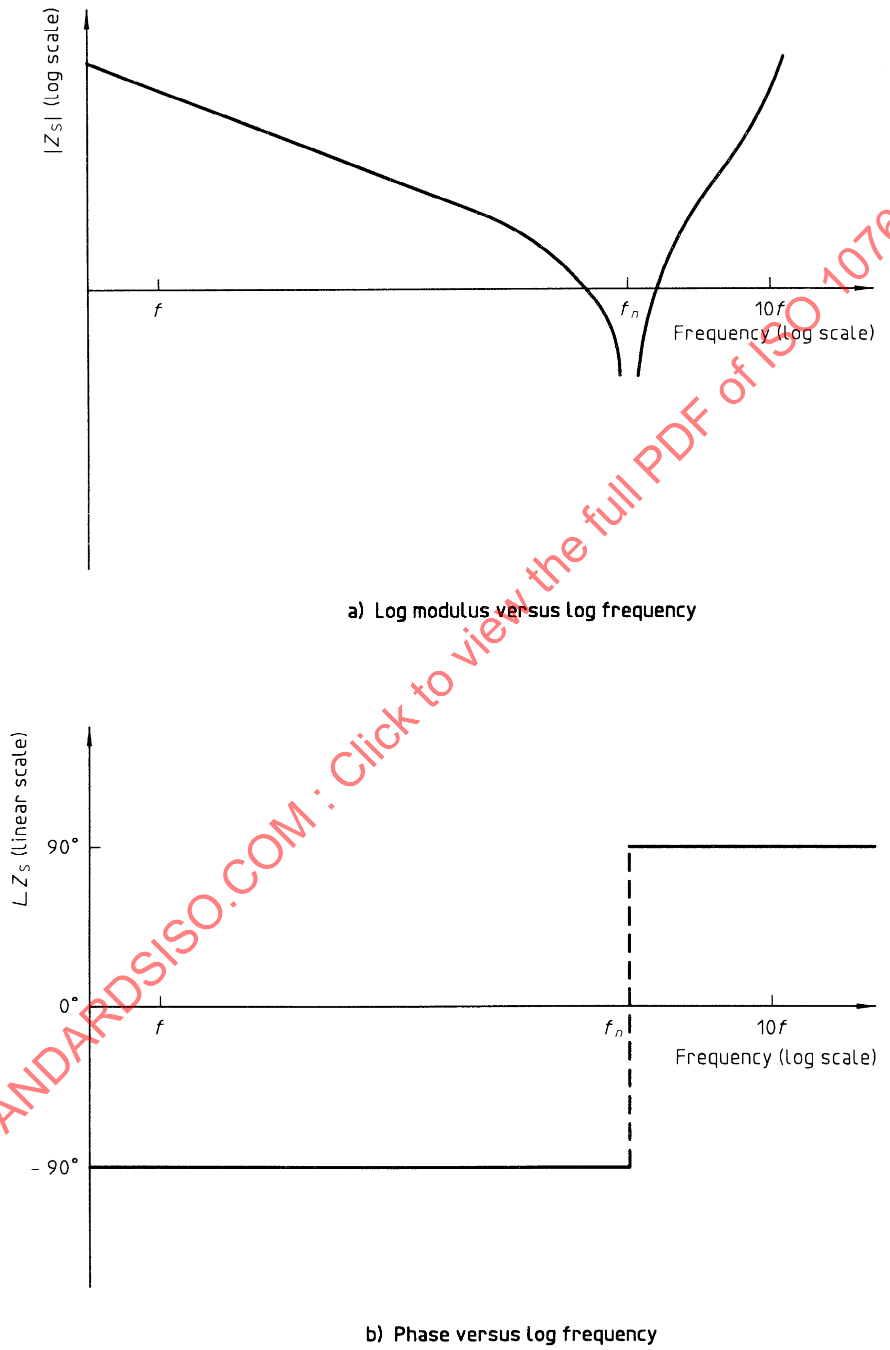
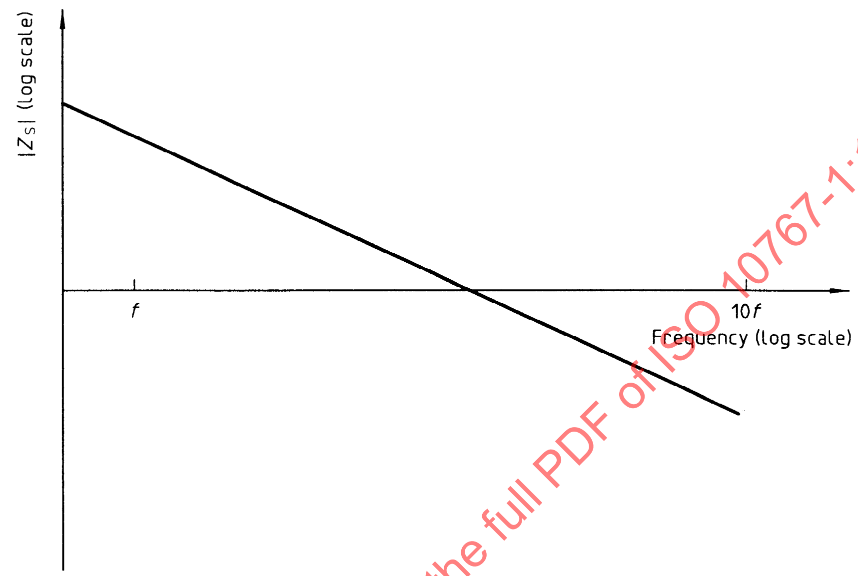
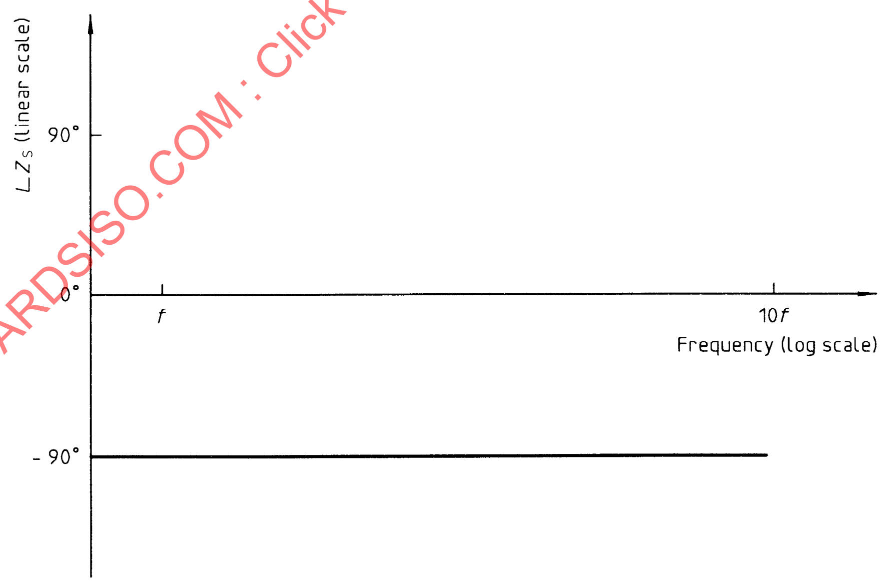



**Figure B.1 — General form of source impedance for distributed-parameter model**




a) Log modulus versus log frequency




b) Phase versus log frequency

**Figure B.2 — General form of source impedance for lumped-parameter model**

### B.6.1 Model 1: Distributed-parameter model

An iterative method is used to apply the model to the experimental results. The modelled source impedance $Z_{SM,i}$ is described by the equation

$$Z_{SM,i} = \frac{c_1}{j \tan(c_2 f_i)} \quad \ldots (B.33)$$

The optimum values of the coefficients $c_1$ and $c_2$ are evaluated in order to minimize the "sum of squared errors" between the model and experimental results, for $n$ harmonics.

Initial estimates of $c_1$ and $c_2$ are required in order to start the iteration. Suitable estimates can be obtained from inspection of the experimental source impedance plots, as follows.

Estimate the frequency $f_n$ (in hertz) of the anti-resonance, at which the amplitude is a minimum and the phase changes from negative to positive. The starting value of $c_2$ is then given by:

$$c_2 = \pi/(2f_n) \quad \ldots (B.34)$$

Estimate the value of the source impedance amplitude [in (N·s)/m$^5$] at the frequency $f_n/2$. Set the starting value of $c_1$ equal to this.

Corrections are then applied to these coefficients as follows, for $k = 1$ to 2:

$$c_{k,NEW} = c_{k,OLD} + \beta \Delta c_k \quad \ldots (B.35)$$

where $\beta$ is a relaxation factor (see B.4.2).

The values of the corrections $\Delta c_1$ and $\Delta c_2$ are obtained by solution of the equations

$$\Delta c_1 = \frac{t_2 s_{1,2} - t_1 s_{2,2}}{s_{1,1} s_{2,2} - s_{2,1} s_{1,2}} \quad \ldots (B.36)$$

$$\Delta c_2 = \frac{t_1 s_{2,1} - t_2 s_{1,1}}{s_{1,1} s_{2,2} - s_{2,1} s_{1,2}} \quad \ldots (B.37)$$

For $n$ harmonics

$$t_k = \sum_{i=1}^{n} \mathrm{Re}(\alpha_i \overline{\sigma_{k,i}}) \quad \ldots (B.38)$$

$$s_{k,l} = \sum_{i=1}^{n} \mathrm{Re}(\overline{\sigma_{k,i}} \sigma_{l,i}) \quad \ldots (B.39)$$

where

$$\alpha_i = jZ_{S,i} \sin(f_i c_{2,OLD}) - c_{1,OLD} \cos(f_i c_{2,OLD}) \quad \ldots (B.40)$$

$$\sigma_{1,i} = -\cos(f_i c_{2,OLD}) \quad \ldots (B.41)$$

$$\sigma_{2,i} = jZ_{S,i} f_i \cos(f_i c_{2,OLD}) + f_i c_{1,OLD} \sin(f_1 c_{2,OLD}) \quad \ldots (B.42)$$

If the following condition is not satisfied for $k = 1$ or 2

$$|\Delta c_k| \leqslant c_{k,OLD} \times 10^{-3} \quad \ldots (B.43)$$

then set $c_{k,OLD}$ equal to $c_{k,NEW}$ for $k = 1$ or 2. Repeat the iteration using equations (B.35) to (B.42) until equation (B.43) is satisfied.