INTERNATIONAL STANDARD

ISO 10767-2

First edition
1999-10-01

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

Part 2:
Simplified method for pumps

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

Partie 2: Méthode simplifiée pour les pompes

Reference number
ISO 10767-2:1999(E)

Contents

International Organization for Standardization
Case postale 56 • CH-1211 Genève 20 • Switzerland
Internet iso@iso.ch

Printed in Switzerland

Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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

International Standard ISO 10767-2 was prepared by Technical Committee ISO/TC 131, *Fluid power systems,* Subcommittee SC 8, *Product testing.*

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*

Annex A forms a normative part of this part of ISO 10767. Annexes B and C are for information only.

Introduction

In hydraulic fluid power systems, power is transmitted and controlled through a liquid under pressure within an enclosed circuit. Hydraulic pumps are devices which convert rotary mechanical power into fluid power. Pump flow has a large, steady component and a smaller, cyclical component superimposed upon it. It is this smaller, cyclical component of the pump flow that reacts with the fluid system of the pump and its circuit, that results in pressure ripple or fluid-borne noise. This fluid-borne noise can be transmitted through the liquid under pressure to other attached components and structures, and can result in unwanted noise and vibrations.

While the flow ripple is the cause of the pressure ripple, it is more difficult to measure. Therefore pressure ripple will be used in this procedure to characterize the fluid-borne noise generation potential of hydraulic fluid power pumps. Pressure ripple is a function of the pump design and the circuit in which it is measured. It is important, therefore, that the test circuit be controlled so as to provide uniform results when comparing the fluid-borne noise generation potential of different types of pumps. Pressure ripple determined in accordance with this part of ISO 10767 may be different to that measured in fluid power systems because of the high impedance of the test line.

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

Part 2:
Simplified method for pumps

1 Scope

This part of ISO 10767 specifies a procedure for measuring the fluid pressure ripple characteristics of hydraulic fluid power pumps with a maximum error of + 1 dB to – 3 B.

ISO 10767-1 can be used if pressure ripple measurements at lower pressure levels, lower frequencies, or at greater accuracy levels is required. This procedure covers a frequency and pressure range that has been found to excite many circuits to emit airborne noise that most concerns designers of hydraulic fluid power systems. It allows the pressure ripple data to be published with minimal calculations and processing of the measured data. This part of ISO 10767 promotes quieter fluid power systems by establishing a uniform procedure for measuring and reporting the fluid pressure ripple characteristics of hydraulic fluid power pumps. Annex B contains a tutorial explanation of the technical basis for this test procedure.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 10767. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 10767 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 1000:1992, *SI units and recommendations for the use of their multiples and of certain other units.*

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

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

ISO 9110-1:1990, *Hydraulic fluid power — Measurement techniques — Part 1: General measurement principles.*

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

3 Terms and definitions

For the purposes of this part of ISO 10767, the fluid power terms and definitions given in ISO 5598, the acoustical terms and definitions given in ISO 10767-1 and the following apply.

3.1
pump outlet port passage length
L_S
average length from the volume exchange cavities of the pump to the entrance of the test line in normal operation at the test conditions specified

3.2
pump outlet port passage diameter
D_S
average diameter of the discharge cavity from the volume exchange cavities of the pump to the entrance of the test line in normal operation at the test conditions specified

4 Symbols and units

4.1 For the purposes of this part of ISO 10767, the symbols given in Table 1 apply.

Table 1 — Symbols

Symbol	Quantity
B	bulk modulus of elasticity of the test fluid
c_0	reference speed of sound in test fluid not corrected for test line elasticity
D_L	inside diameter of test line
$D_{O,min}$	minimum line termination orifice diameter
$D_{O,max}$	maximum line termination orifice diameter
D_S	pump outlet port passage diameter
E	modulus of elasticity of test line material
f_1	fundamental pumping frequency
f_{max}	maximum frequency limit of test procedure
K	orifice flow coefficient, $K = \dfrac{4q}{\pi D_O^2 \sqrt{\Delta p}}$ (1)
L_L	test line length
L_S	pump outlet port passage length
Z	number of pumping chambers per revolution
n	harmonic number n = 1, 2, 3, ...
N	pump shaft speed
P_n	amplitude of n-th harmonic of pressure ripple (i.e. ½ of peak-to-peak)
p_{RMS}	the root mean square (RMS) average of the pressure ripple harmonics from f_1 to f_{max}
p_{max}	maximum pump outlet test pressure
p_{min}	minimum pump outlet test pressure
Δp	orifice pressure drop
q	average pump flow rate
ρ	mass density of test fluid
t	wall thickness of test line
V_S	pump outlet passage volume

4.2 Units used in this part of ISO 10767 are in accordance with ISO 1000.

4.3 Graphic symbols used in this part of ISO 10767 are in accordance with ISO 1219-1 unless otherwise stated.

5 Instrumentation

5.1 The instruments used to measure flow, pressure, drive speed, and oil temperature shall be in accordance with the recommendations in ISO 9110-1.

5.2 Pressure transducers for measuring pressure ripple shall be piezoelectric type transducers capable of accurate measurements from the pump drive shaft frequency up to 10 kHz minimum in accordance with ISO 9110-1.

5.3 The harmonic content of the pressure ripple shall be established as a function of frequency. This may be achieved using a Fast Fourier Transform (FFT) narrow-band spectrum analyzer. The analysis shall produce accurate measurements from drive shaft frequency up to 10 kHz minimum in accordance with ISO 9110-1.

6 General provisions

6.1 Control the average pressure, drive shaft speed, and fluid temperature to a class B accuracy level in accordance with ISO 9110-1.

6.2 Use the test fluid for which pressure ripple data is desired. Make sure that the test fluid is acceptable for use with the test pump.

6.3 Use extra care when installing pump inlet lines to maintain the inlet pressure within the manufacturer's rated conditions and to prevent air from leaking into the circuit.

6.4 "Run-in" the pump in accordance with the manufacturer's recommendations prior to running tests.

6.5 Run the pump to purge air from all lines and circuit components prior to running tests. All test conditions shall be stabilized within the limits specified in 6.1.

6.6 Use extra care to ensure that the operating pressure of the test lines, components, and the test pump does not exceed the manufacturer's ratings. Do not install any additional components to the test circuit because this can affect the accuracy of the measurements.

WARNING — Line pressure is determined by pump flow and the orifice size selected for the test circuit. Incorrect orifice size can result in extreme line pressure. Take the necessary safety precautions to protect both test equipment and personnel from extreme line pressure.

7 Determination of geometric parameters and speed of sound in the test fluid

7.1 Values for D_S and L_S can be obtained in any one of the following ways:

a) using the diameter of the pump outlet port as an approximation of D_S and calculating L_S from titration measurements of the pump outlet port volume V_S using the following equation:

$$L_S \approx \frac{4\,V_S}{\pi\, D_S^2} \qquad (2)$$

NOTE V_S includes all fittings up to the entrance of the test line.

b) from the manufacturer of the test pump;

c) by estimation from the results of a test procedure that measures the internal impedance of the test pump (e.g. ISO 10767-1).

7.2 Values for the speed of sound in the test fluid c_0 and the test fluid mass density ρ can be obtained from the manufacturer of the fluid. The speed of sound in the test fluid can be corrected for the elasticity of the test line using the following equation:

$$c = \sqrt{\frac{1}{\frac{1}{c_0^2} + \frac{(D_L + t)\,\rho}{E_t}}} \qquad (3)$$

7.3 If a value for the speed of sound in the test fluid c_0 is not available from the manufacturer of the fluid it may be estimated using the following equation:

$$c_0 = \sqrt{B/\rho} \qquad (4)$$

8 Valid frequency and pressure range

8.1 The fundamental pumping frequency is f_1. It is the lowest frequency of the pump pressure ripple that can be measured with this test procedure.

$$f_1 = \frac{ZN}{60} \qquad (5)$$

where N is expressed in rotations per minute in order to give f_1 in hertz.

8.2 The minimum pump outlet pressure that can be measured with this test procedure is p_{min}.

$$p_{min} = \frac{2\rho c q}{\pi D_S^2 \tan\left(\frac{2\pi f_1 L_S}{c}\right)} \qquad (6)$$

8.3 The highest frequency that can be measured with this test procedure is 2,5 kHz or f_{max}, whichever is the lower limit. The following equation is used to calculate f_{max}:

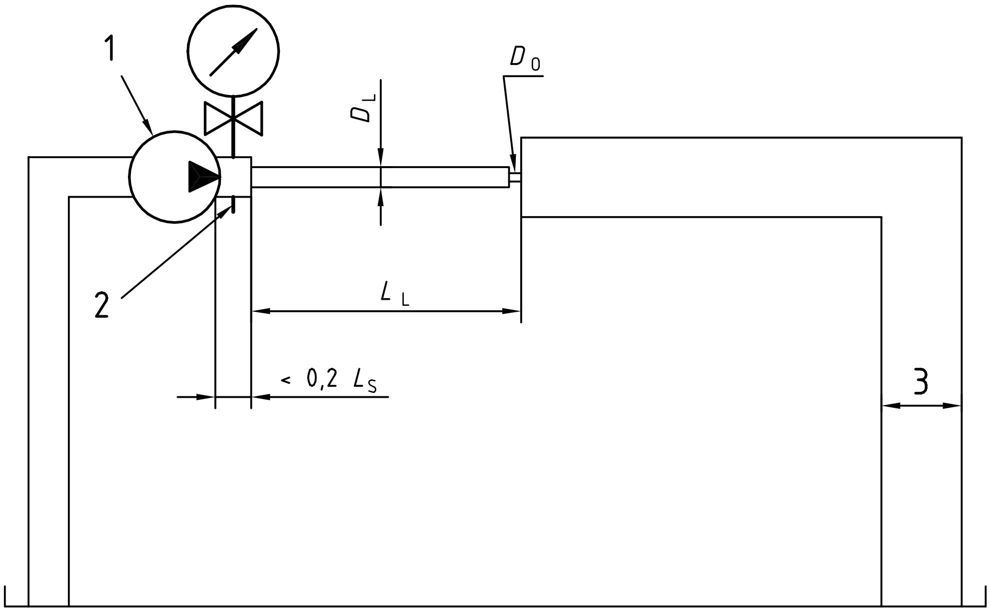
$$f_{max} = \left(\frac{c}{2 L_S}\right) - f_1 \qquad (7)$$

8.4 p_{max} is defined as the maximum pump outlet pressure where pressure ripple data is desired. p_{max} shall be less than the maximum pump outlet pressure allowed by the pump manufacturer and shall comply with the requirements of 6.6.

8.5 Acceptable pressure ripple measurements can be obtained with this test procedure at pump outlet pressures from p_{min} to p_{max} and over a frequency range from f_1 to f_{max} or 2,5 kHz whichever is the lower limit. If the value of p_{min} calculated in 8.2 is greater than p_{max}, valid pressure ripple measurements cannot be obtained using this test procedure.

9 Test circuit

9.1 A test circuit shall be constructed as shown in Figure 1. The test pump can be a single pump, as shown in Figure 1, a multiple stage pump, or may include a boost pump or supercharge pump.



Key

1 Text pump

2 Piezoelectric pressure transducer

3 Inside diameter $> 5D_L$

NOTE Pipeline and orifice symbols are for illustrative purposes only and are not in accordance with ISO 1219-1.

Figure 1 — Schematic diagram of test circuit.

9.2 The transition from the pump outlet port to the entrance of the test line shall be completed within a distance of less than 20 % of the pump outlet port passage length L_S. Install the pressure transducer and pressure gauge between the pump outlet port and the entrance to the test line.

If the transition from outlet port to the entrance of the test line cannot be achieved within the distance specified, then this part of ISO 10767 does not apply. ISO 10767-1 may be a suitable alternative.

9.3 Mount the pressure transducer so that its sensing surface faces upward and is essentially tangential to the flow stream.

9.4 The outlet pressure gauge shall be shut off from the test circuit when making pressure ripple measurements. The gauge shut-off valve shall be located as close as possible to the test line to minimize branch circuit interactions.

9.5 The test line between the pump and the termination orifice shall be steel tubing with an inside diameter estimated using the following equation:

$$D_L = \sqrt{\frac{4\rho c q}{\pi(p_{max} + p_{min})}} \tag{8}$$

A tubing inside diameter shall be chosen that is equal to D_L or the next smaller standard tubing size. The wall thickness of the tubing shall be chosen to comply with the operating pressure requirements given in 6.6.

9.6 The test line length L_L, as shown in Figure 1, shall be within the following limits:

$$0{,}9L_S \leqslant L_L \leqslant 1{,}1L_S \tag{9}$$

9.7 Determine the maximum test line termination orifice diameter using the following equation:

$$D_{O,max} = \sqrt{\frac{4q}{\pi\ K\sqrt{p_{min}}}} \tag{10}$$

Testing with this orifice diameter will yield pump outlet pressure approximately equal to p_{min}

9.8 Determine the minimum test line termination orifice diameter using the following equation:

$$D_{O,min} = \sqrt{\frac{4q}{\pi\ K\sqrt{p_{max}}}} \tag{11}$$

Testing with this orifice diameter will yield pump outlet pressures approximately equal to p_{max}.

9.9 The termination orifice shall be located at the entrance to the fitting at the downstream end of the test line. Care should be taken not to create any significant oil volume cavities between the end of the test line and the entrance to the termination orifice.

9.10 The line downstream of the termination orifice shall have an inside diameter greater than $5D_L$.

10 Test procedure

10.1 Install the test line termination orifice with diameter $D_{O,max}$ as determined in 9.7.

10.2 With the pressure gauge shut-off valve opened, adjust the pump drive speed and inlet oil temperature to the desired test values.

10.3 Measure and record the actual average pump outlet port pressure.

10.4 Close the pressure gauge shut-off valve.

10.5 Measure the harmonic content of the pressure ripple. Record only the first 10 harmonics of pumping frequency. Establish the peak amplitude of each harmonic. Discard any harmonics above 2,5 kHz or f_{max}, whichever is the lower limit.

10.6 Shut down the test pump and install the test line termination orifice diameter $D_{O,min}$ as determined in 9.9 and repeat 10.2 to 10.5.

10.7 If pressure ripple data at an average pump outlet pressure between p_{min} and p_{max} is desired, choose as many intermediate test line termination orifice diameters as desired between $D_{O,max}$ and $D_{O,min}$ and repeat 10.2 to 10.5 with each orifice.

10.8 If pressure ripple data at other test conditions (i.e. drive speeds, pump displacements, oil temperatures, etc.) is required, calculate a new test line diameter according to 9.5 and termination orifice diameters according to 9.7 and 9.8 and repeat 10.2 to 10.7. The requirements of 8.2, 8.3 and 8.4 shall be met with each corresponding test line diameter, termination orifice, and operating condition.

11 Data presentation

11.1 Report the harmonics of pumping frequency obtained in 10.5 for each pump operating condition. This data shall be reported as the amplitude (i.e. 1/2 of the peak-to-peak value) of the pressure ripple.

11.2 Calculate the overall RMS average pressure ripple amplitude for the integral harmonics of pumping frequency from f_1 to f_{max} or 2,5 kHz (whichever is the lower) for each pump operating condition of 11.1. Do not include pressure ripple measurements above the tenth harmonic of pumping frequency. This can be calculated using the following equation:

$$p_{\mathrm{RMS}} = \sqrt{\frac{P_1^2 + P_2^2 + P_3^2 + \ldots + P_n^2}{2}} \qquad (12)$$

11.3 All pressure ripple measurements and test conditions shall be expressed in units in accordance with ISO 1000.

11.4 The test information and conditions shall be reported using the forms given in annex A.

12 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:

"Fluid borne noise characteristics of this pump were obtained and are presented in accordance with ISO 10767-2:1999, *Hydraulic fluid power — Determination of pressure ripple levels generated in systems and components — Part 2: Simplified method for pumps."*

Annex A
(normative)

Test report forms

A.1 Pump pressure ripple test information form

Description of pump: ....

Model or identification number: ....

Serial number: ....

Part number: ....

Name of manufacturer: ....

Address of manufacturer: ....

Name of testing organization: ....

Address of testing organization: ....

Date of test: ....

Location of test: ....

A.2 Pump pressure ripple test conditions form

Test fluid description ....

Pump inlet oil temperature ....

Speed of sound in test fluid (corrected) c = ...

Reference speed of sound in test fluid (uncorrected)

c_0 = ...

Density of test fluid ρ = ...

Drive shaft speed N = ...

Pump outlet flow q = ...

Pump outlet port passage diameter D_S = ...

Pump outlet port passage length L_S = ...

Method used to obtain D_S and L_S (see 7.1)..

Number of pumping chambers Z = ...

Test line internal diameter D_L = ...

Test line length L_L = ...

Test line wall thickness t = ...

Test line material modulus of elasticity E = ...

Termination orifice diameters $D_{O,max}$ = ...

$D_{O,min}$ = ...

Other: ....

Test pressures p_{min} = ...

p_{max} = ...

Other: ....

Fundamental pumping frequency f_1 = ...

Maximum frequency f_{max} = ...

A.3 Pump pressure ripple test results form

Drive shaft speed: ....

Test pressure: ....

Pump inlet oil temperature: ....

P_1 = ...

P_2 = ...

P_3 = ...

P_4 = ...

P_5 = ...

P_6 = ...

P_7 = ...

P_8 = ...

P_9 = ...

P_{10} = ...

p_{RMS} = ...

Annex B
(informative)

Tutorial explanation of the basis for the test procedure given in this part of ISO 10767 for measuring pump pressure ripple

Introduction

This part of ISO 10767 has been developed as a test method to provide an unbiased pump pressure ripple measurement directly from a simple test. This part of ISO 10767 is similar to ANSI/(NFPA) T 2.7.2:1995 [7] which is a method suitable for measuring the pressure ripple of many commonly used industrial hydraulic pumps. It does not cover as broad a frequency range and pressure range as this part of ISO 10767 but it will yield valid comparative data on which to make selections of pumps where fluid-borne noise is a concern. It is also possible for the method specified in this part of ISO 10767 to be conducted with the test pump operating in a modified version of its intended application for comparison with manufacturer's laboratory measurements.

ISO 10767-1 (the precision method) requires more specialized laboratory test equipment and an additional pump or pressure ripple source to provide measurements that allow the test pump pressure ripple, flow ripple, internal impedance, and the speed of sound in the test fluid to be calculated. Because of the nature of the required complex calculations, ISO 10767-1 is best suited for use in a laboratory with computer based data acquisition and analysis equipment.

B.1 Additional Symbols

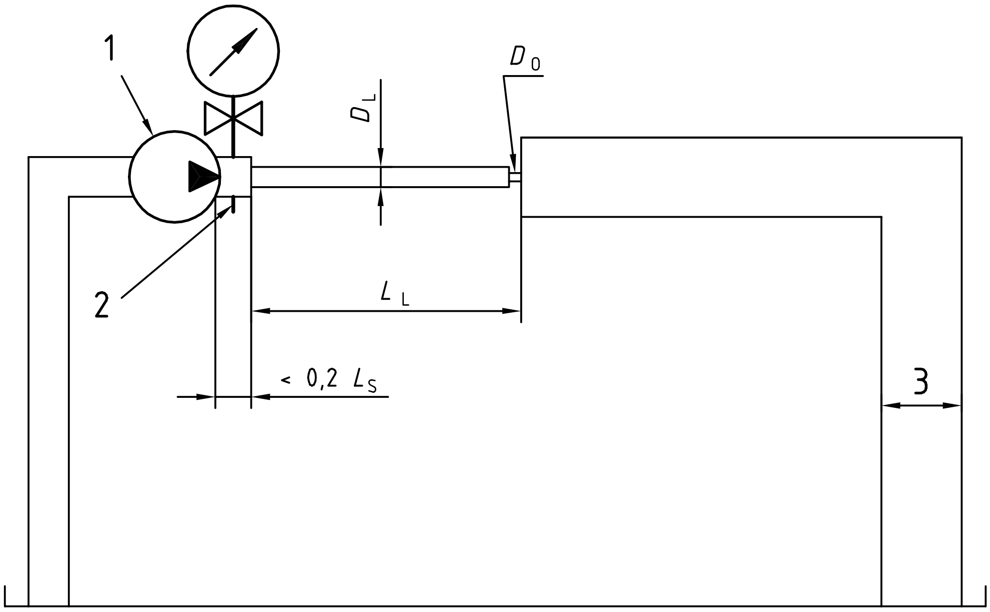
f	frequency, in hertz (Hz)
j	imaginary unit vector ($\sqrt{-1}$)
P_B	theoretical blocked pressure ripple amplitude
P_E	pressure ripple amplitude at the entrance to a test pipe
p	average pump outlet pressure
p^*	rated average pump outlet pressure
Q_S	pump flow ripple amplitude
$\Delta q(p^*)$	average pump flow loss at rated average outlet pressure
ω	frequency, in radians per second (rad/s)
x	distance along a transmission line
Z_E	entry impedance of a transmission line with a termination impedance
Z_0	characteristic impedance of test pipe
Z_{0S}	characteristic impedance of pump outlet chamber
Z_S	pump internal impedance
Z_T	termination orifice impedance
Z_{TS}	termination leakage impedance of pump

NOTE See Table 1 for symbols not listed above.

B.2 Description of the ISO 10767-2 test procedure

This part of ISO 10767 is based on the assumption that a short, small diameter (but standard size) steel tube and orifice can be connected to the pump outlet port that will allow the measured pressure ripple to be independent of the test circuit and only dependent upon the pressure ripple generation characteristics of the test pump. This will only be true when the combined impedance Z_E of the tube and orifice is large relative to the internal impedance Z_S of the test pump.

The recommended test circuit is shown schematically in Figure B.1.



Key

1 Text pump

2 Piezoelectric pressure transducer

3 Inside diameter $> 5D_L$

NOTE Pipe-line and orifice symbols are for illustrative purposes only and are not in accordance with ISO 1219-1.

Figure B.1 — Schematic diagram of test circuit

Figure B.2 shows the impedance representation proposed by Bowns, Edge and Tilley [1] of the hydraulic circuit shown in Figure B.1.

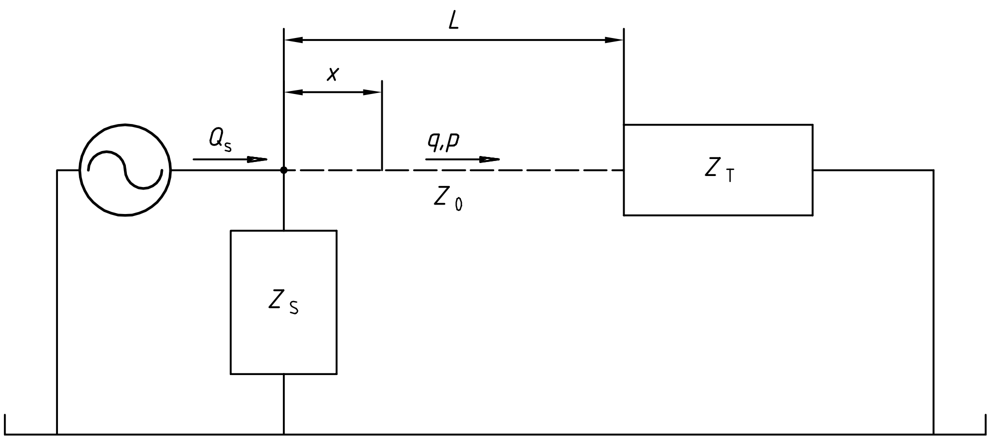


Figure B.2 — Impedance representation of hydraulic circuit

Distances x and L in Figure B.2 are intended to represent measurements along a transmission line with a characteristic impedance Z_0 that is connected between the pump outlet port and a termination orifice Z_T. The internal impedance of the pump is represented by Z_S.

By differentiating the equation for pressure drop across an orifice it can be shown that the termination orifice impedance is given by equation (B.1):

$$Z_T = \frac{2p}{q} \tag{B.1}$$

Equation (B.1) has been independently verified in tests performed by both Claar [2] and Theissen [3] on adjustable throttling valves at frequencies up to 450 Hz. McCandish, Edge and Tilley [4] have shown that the impedance of such a throttling valve can be lower than that described by equation (B.1) at high frequency, but it is felt that this effect was probably due to the volume chamber typically found at the entrance of such valves. Steps have been taken in this part of ISO 10767 to avoid such volume chambers at the entry to the termination orifice Z_T. With such precautions, equation (B.1) has been shown to be valid up to 4 kHz and suitable for pressure ripple measurements to that frequency.

Keller [5] defines the impedance of a hydraulic transmission line of length L_L, characteristic impedance Z_0, and termination impedance Z_T with equation (B.2):

$$Z_E = Z_0 \left[\frac{Z_T \cos\left(\frac{\omega L_L}{c}\right) + j Z_0 \sin\left(\frac{\omega L_L}{c}\right)}{Z_0 \cos\left(\frac{\omega L_L}{c}\right) + j Z_T \sin\left(\frac{\omega L_L}{c}\right)} \right] \tag{B.2}$$

If the pressure drop along the transmission line and the leakage from the line are assumed to be zero, Z_0 can be calculated from equation (B.3):

$$Z_0 = \frac{4\rho c}{\pi D_L^2} \tag{B.3}$$

Edge [6] has shown that the internal impedance of the pump Z_S behaves like a short transmission line and has the same form as equation (B.2). The pump internal impedance can be calculated using equation (B.4) if it is assumed that the pump characteristic impedance Z_{0S} is based on an apparent diameter D_S of the pump's discharge passageway, the transmission line length is based on the apparent length L_S of this passageway, and the termination impedance Z_{TS} is based on the ratio of the average pump outlet pressure to the average flow loss at that pressure (i.e. based on the pump's volumetric efficiency).

$$Z_S = Z_{0S} \left[\frac{Z_{TS} \cos\left(\frac{\omega L_S}{c}\right) + j Z_{0S} \sin\left(\frac{\omega L_S}{c}\right)}{Z_{0S} \cos\left(\frac{\omega L_S}{c}\right) + j Z_{TS} \sin\left(\frac{\omega L_S}{c}\right)} \right] \tag{B.4}$$

where

$$Z_{0S} = \frac{4\rho c}{\pi \; {D_S}^2} \tag{B.5}$$

and

$$Z_{TS} = \frac{p^*}{\Delta q \; (p^*)} \tag{B.6}$$

An impedance representation of this circuit that includes the transmission line effects can be drawn as shown in Figure B.3.

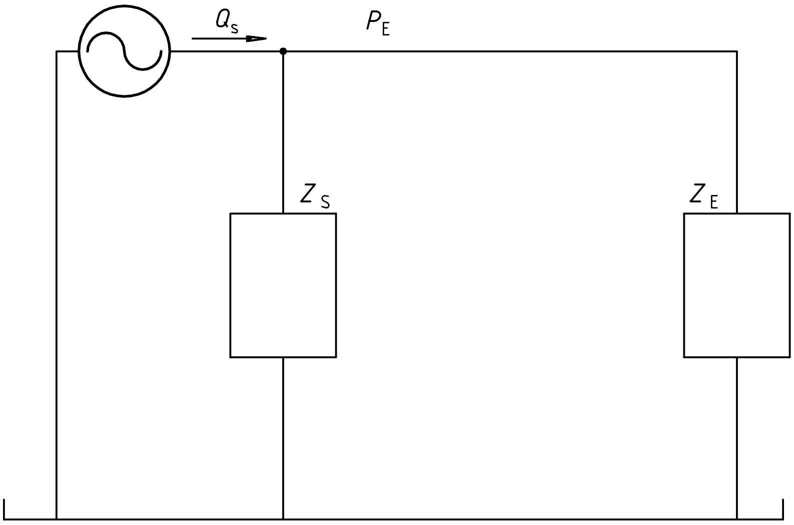


Figure B.3 — Impedance representation of circuit including transmission line effects

The pressure ripple at the outlet of the pump (i.e. at the entrance of the transmission line connected to the outlet) can be calculated using equation (B.7):

$$P_E = \frac{Q_S Z_S Z_E}{Z_S + Z_E} \quad \text{(B.7)}$$

The product of $Q_S Z_S$ is the pressure ripple that would be developed at the pump outlet port if Z_E was infinitely high (equivalent to blocking the outlet port). The ratio of the pressure ripple measured at the outlet of the pump P_E to the theoretical blocked pressure P_B can be obtained by rearranging equation (B.7):

$$\frac{P_E}{P_B} = \frac{Z_E}{Z_S + Z_E} \quad \text{(B.8)}$$

where

$$P_B = Q_S Z_S \quad \text{(B.9)}$$

The pressure ripple ratio P_E/P_B of equation (B.8) depends only on the relative complex values of the entry impedance of the transmission line connected to the pump outlet port Z_E and the pump internal impedance Z_S. If Z_E is much larger than Z_S, then the pressure ripple ratio is nearly equal to 1 (i.e. 0 dB) and the pressure ripple measured at the pump outlet port is nearly equal to the theoretical blocked pressure P_B. This condition where $Z_E > Z_S$ will be subsequently referred to throughout the remainder of the annex as "low error". If we could obtain an independent measurement of Z_S, then the pump flow ripple Q_S could be calculated from equation (B.9).

These relationships in a typical pump circuit are shown graphically in Figure B.4.

In this circuit, the pipe inside diameter D_L is about 1,1 times the apparent diameter of the pump outlet port chamber D_S and the length L_L of this pipe is about 4,6 times the apparent length of the pump outlet chamber L_S. Such an outlet circuit would be common for typical customer installations of such a pump. There are two frequency ranges where the magnitude of the test circuit entry impedance Z_E is less than the pump impedance Z_S. These two ranges are from 0,02 kHz to 1,2 kHz and from 1,75 kHz to 2,25 kHz. In these ranges the measured pressure ripple error is very large. Even over the remainder of the frequency range where Z_E is larger than Z_S, it is not large enough to yield a low error.

If the outlet pipe is shortened to about 2,7 L_S but with the same inside diameter, the critical frequency ranges are shifted to higher values, but the error remains high as shown in Figure B.5.

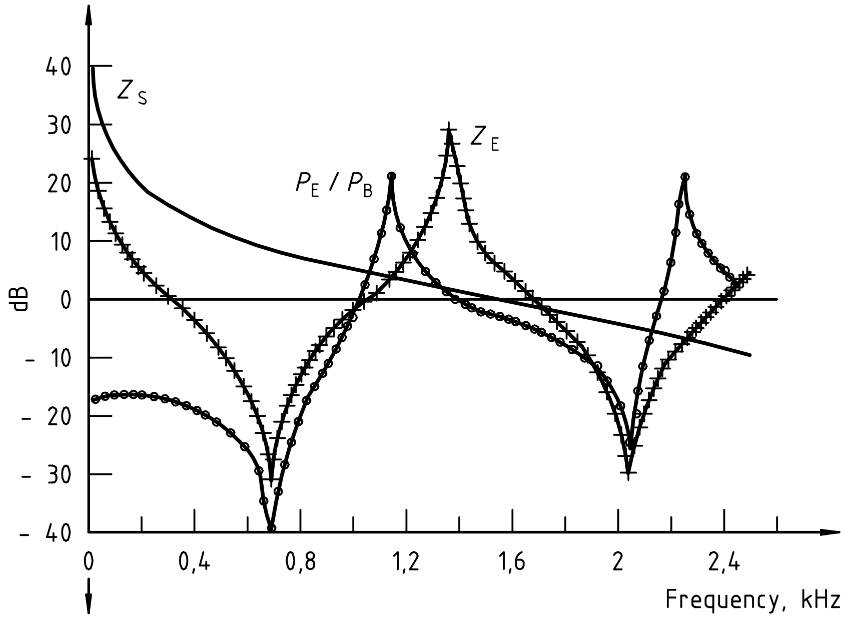


Figure B.4 — Effect of complex values of entry impedance on pressure ripple ratio

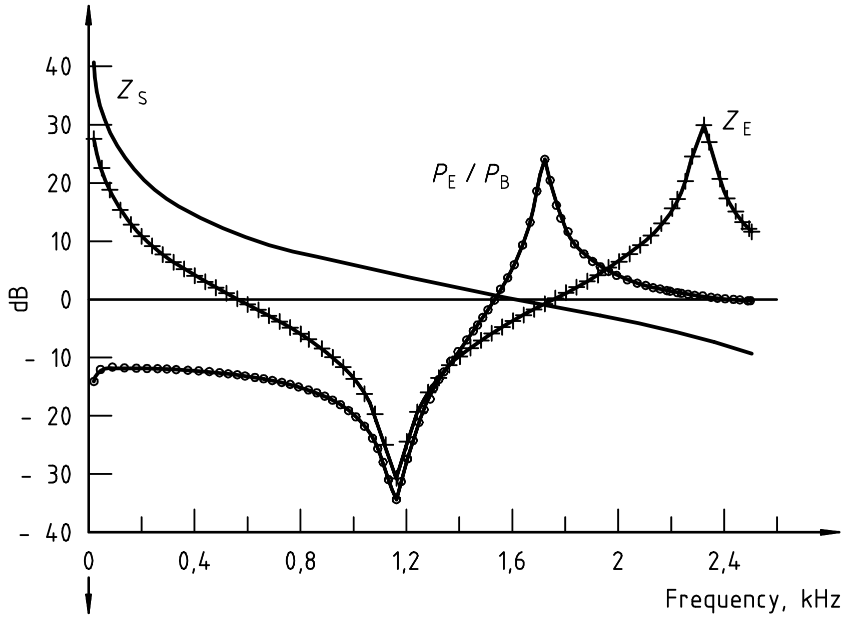


Figure B.5 — Effect of higher frequencies

By observing the trends in Figures B.4 and B.5, it is apparent that making the test pipe shorter makes the curves of Z_E and Z_S more nearly parallel. In fact, if L_L is made equal to L_S, the Z_E and Z_S curves will be nearly parallel with identical critical frequencies. Furthermore, if $D_L = D_S$ and $L_L = L_S$ then Z_E would have a similar shape and magnitude as Z_S at all frequencies. In this case, the shape of Z_E and Z_S would only differ by the magnitude of their respective termination impedances.

The form of equations (B.2) and (B.3) causes the magnitude of Z_E to be large relative to Z_S when the pipe inside diameter D_L is much smaller than D_S. Selecting a small diameter, short test pipe will therefore yield a test circuit with low error. Figure B.6 shows the effect of choosing a pipe of diameter where D_L = 0,28D_s and length L_L = 1,0L_S.

Figure B.6 shows that the difference between the pressure ripple measured at the pump outlet port and the theoretical blocked pressure ripple is very small from about 100 Hz up to the maximum value shown in the graph of 2,5 kHz.

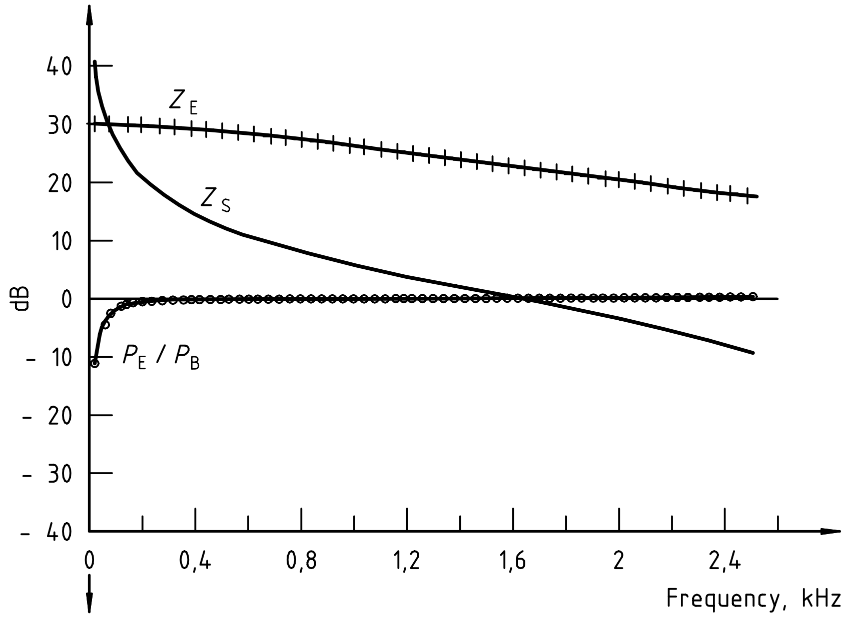


Figure B.6 — Comparison of measurements of pump outlet and blocked pressure ripple

This is the principle used in this part of ISO 10767. The test pipe diameter is chosen in 9.5 so that its characteristic impedance Z_0 is equal to the termination orifice impedance Z_T at the average pump outlet test pressure.

$$Z_0 = Z_T \tag{B.10}$$

$$\frac{4\rho c}{\pi D_L^2} = \frac{2p}{q} \tag{B.11}$$

$$D_L = \sqrt{\frac{2\rho c q}{\pi p}} \tag{B.12}$$

The test procedure allows a range of pressures from p_{min} to p_{max} with a single pipe diameter. The equation in 9.5 uses $(p_{min} + p_{max})/2$ as the pressure where $Z_0 = Z_T$. Substituting this average test pressure for p in equation (B.12) yields:

$$D_L = \sqrt{\frac{4\rho c q}{\pi \ (p_{min} + p_{max})}} \tag{B.13}$$

Choosing the pipe diameter in this way has the effect of increasing the magnitude of Z_E relative to Z_S and keeping the variations of Z_E as a function of frequency relatively small. Figure B.7 is a graph of equation (B.13) for a range of pipe diameters D_L from 2 mm to 32 mm. The values used in Figure B.7 for the speed of sound c and fluid mass density ρ were 1 302 m/s and 908 kg/m^3 respectively.

The test pipe length is chosen in 9.6 so that the first anti-resonance of the test pipe coincides with the first anti-resonance of the pump internal impedance; that is where $L_L = L_S$. This makes the critical frequencies of Z_E and Z_S equal, reducing the number of times that these two curves can intersect and thereby reducing measurement error.

The minimum pressure p_{min} of paragraph 8.2 is the pump outlet pressure below which the magnitude of the pressure ripple ratio of equation (B.8) is greater than – 3 dB at the fundamental pumping frequency f_1. Similarly, the upper frequency limit of f_{max} in 8.3 is the frequency above which the magnitude of the pressure ripple ratio is greater than – 3 dB at a pump outlet pressure of p_{min}. The derivations of the minimum pressure and maximum frequency equations are described in clause B.3.

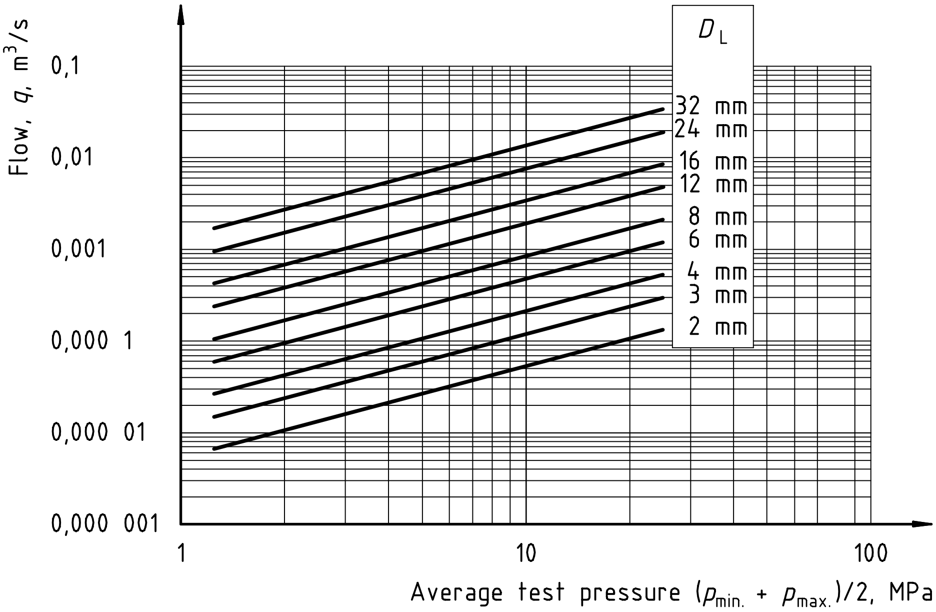


Figure B.7 — Flow vs. average test pressure for a range of pipe diameters

The root mean square (RMS) average pressure ripple as a function of the average pump outlet pressure for an axial piston pump tested according to an early version of this part of ISO 10767 is shown in Figure B.8. It displays the overall RMS average value of all of the harmonics of the measured pump pressure ripple from the fundamental frequency to 4 kHz. The two lines on this graph are for data taken at drive shaft speeds of 1 500 r/min and 1 800 r/min.

The spectral distribution of this pressure ripple data and knowledge of the pump internal impedance are theoretically all that is necessary to predict the pump pressure ripple in other defined impedance circuits.

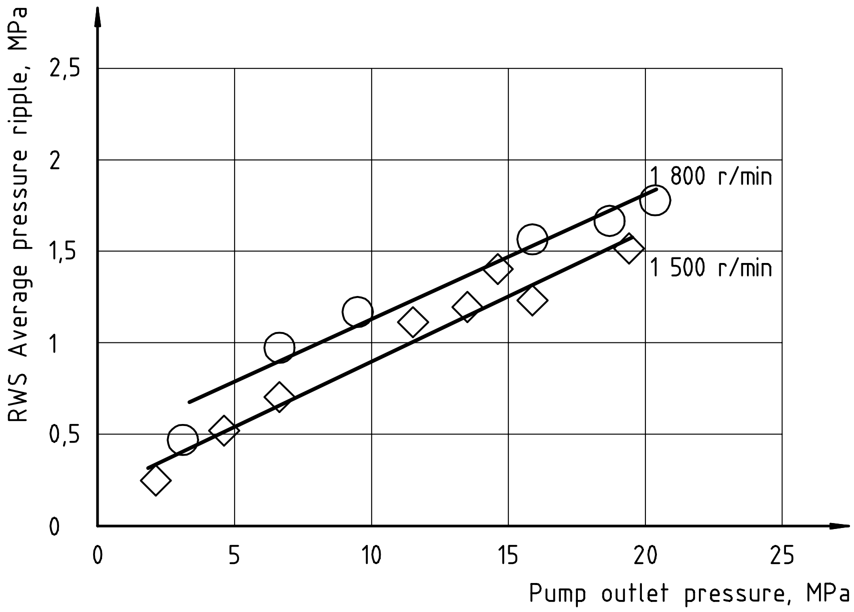


Figure B.8 — RMS average pressure ripple vs. pump outlet pressure

B.3 Valid measurement range

The ratio of the pressure ripple measured at the outlet of the pump to the theoretical blocked pressure ripple from equation (B.8) is:

$$\left|\frac{P_E}{P_B}\right| = \frac{Z_E}{Z_E + Z_S} \tag{B.14}$$

Allowing for a maximum – 3 dB error between the measured pressure ripple P_E and the blocked pressure ripple P_B yields:

$$\left|\frac{P_E}{P_B}\right| = \frac{1}{\sqrt{2}} \tag{B.15}$$

Combining equations (B.14) and (B.15) yields:

$$\left|\frac{Z_E}{Z_E + Z_S}\right| = \frac{1}{\sqrt{2}} \tag{B.16}$$

The entry impedance Z_E of a line terminated by an orifice is approximately equal to its termination impedance Z_T, at frequencies near the line resonant frequency, when the line termination impedance Z_T is nearly equal to the transmission line characteristic impedance Z_0.

$$Z_E \approx \frac{2p}{q} \tag{B.17}$$

The general equation for the pump internal impedance Z_S from equation (B.4) is:

$$Z_S = Z_{0S}\left[\frac{Z_{TS}\cos\left(\frac{\omega L_S}{c}\right) + j\,Z_{0S}\sin\left(\frac{\omega L_S}{c}\right)}{Z_{0S}\cos\left(\frac{\omega L_S}{c}\right) + j\,Z_{TS}\sin\left(\frac{\omega L_S}{c}\right)}\right] \tag{B.18}$$

If the volumetric efficiency of the pump is high (i.e. when $Z_{TS} >> Z_{0S}$). The pump impedance Z_S can then be simplified as follows:

$$Z_S = Z_{0S}\left[\frac{\cos\left(\frac{\omega L_S}{c}\right) + j\,\frac{Z_{0S}}{Z_{TS}}\sin\left(\frac{\omega L_S}{c}\right)}{\frac{Z_{0S}}{Z_{TS}}\cos\left(\frac{\omega L_S}{c}\right) + j\sin\left(\frac{\omega L_S}{c}\right)}\right] \tag{B.19}$$

$$Z_S = Z_{0S}\left[\frac{\cos\left(\frac{\omega L_S}{c}\right)}{j\sin\left(\frac{\omega L_S}{c}\right)}\right] \tag{B.20}$$

$$Z_S = \frac{4\rho c}{\pi D_S^2\; j\tan\left(\frac{\omega L_S}{c}\right)} \tag{B.21}$$

Equation (B.21) for Z_S is a periodic function of frequency that reaches a maximum when:

$$\frac{\omega_{n,\max} L_S}{c} = n\,\pi \tag{B.22}$$

where

$n = 0, 1, 2, 3, \dots, \infty$

Solving equation (B.22) for frequency yields:

$$\omega_{n,\max} = \frac{n \pi c}{L_S} \tag{B.23}$$

It is slightly above and below these maximum value frequencies $\omega_{n,\max}$ where the error is equal to – 3 dB. In order to calculate the pump outlet pressure where the error is equal to – 3 dB, equations (B.17) and (B.21) are substituted into equation (B.16).

$$\left| \frac{\dfrac{2p}{q}}{\dfrac{2p}{q} + \dfrac{4\rho c}{\pi D_S^2 \, j \tan\left(\dfrac{\omega L_S}{c}\right)}} \right| = \frac{1}{\sqrt{2}} \tag{B.24}$$

$$\frac{\sqrt{\left(\dfrac{2p}{q}\right)^2}}{\sqrt{\left(\dfrac{2p}{q}\right)^2 + \left(\dfrac{4\rho c}{\pi D_S^2 \tan\left(\dfrac{\omega L_S}{c}\right)}\right)^2}} = \frac{1}{\sqrt{2}} \tag{B.25}$$

$$\frac{\left(\dfrac{2p}{q}\right)^2}{\left(\dfrac{2p}{q}\right)^2 + \left(\dfrac{4\rho c}{\pi D_S^2 \tan\left(\dfrac{\omega L_S}{c}\right)}\right)^2} = \frac{1}{2} \tag{B.26}$$

$$\left(\frac{2p}{q}\right)^2 = \left(\frac{4\rho c}{\pi D_S^2 \tan\left(\dfrac{\omega L_S}{c}\right)}\right)^2 \tag{B.27}$$

$$\frac{2p}{q} = \frac{4\rho c}{\pi D_S^2 \tan\left(\dfrac{\omega L_S}{c}\right)} \tag{B.28}$$

$$p = \frac{2\rho c q}{\pi D_S^2 \tan\left(\dfrac{\omega L_S}{c}\right)} \tag{B.29}$$

At the fundamental pumping frequency f_1, the minimum pump outlet test pressure for a – 3 dB difference between the measured pressure ripple and the blocked pressure ripple is:

$$p_{\min} = \frac{2\rho c q}{\pi D_S^2 \tan\left(\dfrac{2\pi f_1 L_S}{c}\right)} \tag{B.30}$$

At any pump outlet pressure greater than or equal to p_{min}, the error remains less than – 3 dB from f_1 up to a frequency slightly below the second resonant frequency of the pump internal impedance. This is the next higher frequency above f_1 where the difference between the measured pressure ripple again differs from the blocked pressure ripple by more than – 3 dB. This maximum frequency f_{max} is below the second resonant frequency of the pump internal impedance by an amount equal to f_1 and can be calculated with equation (B.31).

$$f_{max} = \left(\frac{c}{2L_S}\right) - f_1 \tag{B.31}$$

Pressure ripple measurements over the pump outlet pressure range from p_{min} to p_{max} and over the frequency range from f_1 to f_{max} will yield values that are equal to the theoretical blocked pressure ripple with a maximum negative error of – 3 dB. A small positive error is also possible at pump outlet pressures below $p_{max}/2$. Based on numerical simulations of the test procedure, the positive error is limited to about + 1 dB. The general form of the ratio of the measured pressure ripple to the theoretical blocked pressure ripple for this part of ISO 10767 is shown as a function of frequency in Figure B.9.

The maximum positive error is reduced to 0 dB when the test pressure is equal to or greater than $p_{max}/2$. The maximum total error is therefore, between 0 dB to – 3 dB at test pressures equal to or greater than $p_{max}/2$ and between +1 dB to – 3 dB at pressures less than $p_{max}/2$.

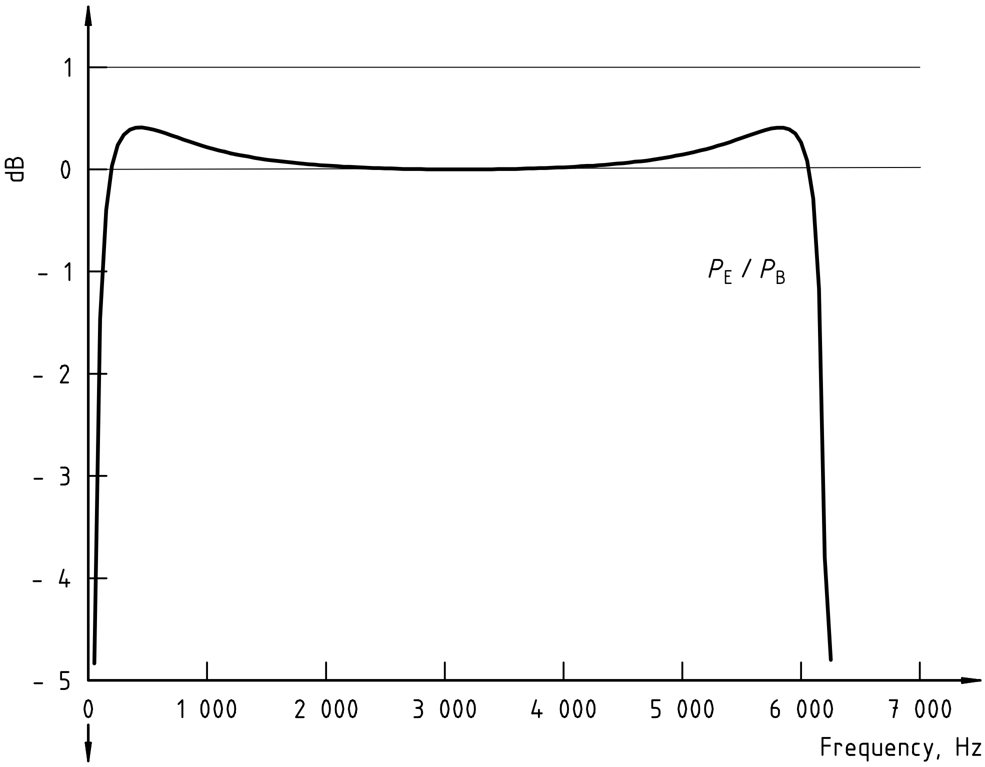


Figure B.9 — Form of ratio of measured pressure ripple to blocked pressure ripple

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