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

Part 1:
Introduction

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

Partie 1: Introduction

Reference number
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Foreword

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International Standard ISO 15086-1 was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 8, *Product testing*.

ISO 15086 consists of the following parts, under the general title *Hydraulic fluid power — Determination of fluid-borne noise characteristics of components and systems*:

— *Part 1: Introduction*

— *Part 2: Measurement of the speed of sound in a fluid in a pipe*

Introduction

The airborne noise emitted by hydraulically actuated equipment is the result of simultaneous acoustic radiation from all mechanical structures comprising the machine. The contribution from individual components generally forms only a small part of the total acoustic energy radiated. Acoustic intensity measurement techniques have demonstrated that the pulsating energy in the hydraulic fluid (fluid-borne noise) is the dominant contributor to machine noise. In order to develop quieter hydraulic machines it is therefore necessary to reduce this hydro-acoustic energy.

Various approaches have been developed to describe the generation and transmission of fluid-borne noise in hydraulic systems. Of these, the transfer matrix approach has the merit of providing a good description of the physical behaviour as well as providing an appropriate basis for the measurement of component characteristics.

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

Part 1:
Introduction

1 Scope

This part of ISO 15086 provides a general introduction to transfer matrix theory, which allows the determination of the fluid-borne noise characteristics of components and systems. It also provides guidance on practical aspects of fluid-borne noise characterization.

This part of ISO 15086 is applicable to all types of hydraulic fluid power circuits operating under steady-state conditions for fluid-borne noise over an appropriate range of frequencies.

2 Normative reference

The following normative document contains provisions which, through reference in this text, constitute provisions of this part of ISO 15086. 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 15086 are encouraged to investigate the possibility of applying the most recent editions of the normative document 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 5598, *Fluid power systems and components — Vocabulary*

3 Terms and definitions

For the purposes of this part of ISO 15086, the terms and definitions given in ISO 5598 and the following apply.

3.1
flow ripple
fluctuating component of flow rate in a hydraulic fluid, caused by interaction with a flow ripple source within the system

3.2
pressure ripple
fluctuating component of pressure in a hydraulic fluid, caused by interaction with a flow ripple source within the system

3.3
hydraulic noise generator
hydraulic component generating flow ripple and consequently pressure ripple in a circuit, or hydraulic component generating pressure ripple and consequently flow ripple in the circuit

3.4
fundamental frequency
lowest frequency of pressure (or flow) ripple considered in a theoretical analysis or measured by the frequency-analysis instrument

EXAMPLE 1 A hydraulic pump or motor with a shaft frequency of N revolutions per second may be taken to have a fundamental frequency of N Hz. Alternatively, for a pump or motor with k displacement elements, the fundamental frequency may be taken to be Nk Hz, provided that the measured behaviour does not deviate significantly from cycle to cycle.

EXAMPLE 2 A digital frequency analyzer has a fundamental frequency defined by the frequency of the first spectral line.

3.5
harmonic
sinusoidal component of the pressure ripple or flow ripple occurring at an integer multiple of the fundamental frequency.

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

3.6
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

NOTE Impedance may be expressed in terms of its amplitude and phase or alternatively by its real and imaginary parts.

3.7
admittance
reciprocal of impedance

3.8
characteristic impedance of a pipeline
impedance of an infinitely long pipeline of constant cross-sectional area

3.9
wavelength
ratio of the speed of sound to the frequency of interest (in hertz)

3.10
anechoic
without reflection

NOTE With reference to a condition in which a travelling wave is propagated but no energy is reflected back in the direction of propagation.

3.11
hydro-acoustic energy
fluctuating part of the energy in a liquid

3.12
broad-band fluid-borne noise
hydro-acoustic energy distributed over the frequency spectrum

3.13
port-to-port symmetry
property of a two-port component in which the wave propagation characteristics remain the same when its port connections to the circuit are reversed

4 Symbols

The following symbols are used in this part of ISO 15086.

A, A', A^*	Complex coefficient
B, B', B^*	Complex coefficient
C'	Complex coefficient
c	Acoustic velocity
d	Internal diameter of pipe
f	Frequency (hertz)
f_0	Fundamental frequency (hertz)
j	Complex operator
L	Distance along pipe
n	Total number of harmonics
P	Fourier transform of pressure ripple
$p(t)$	Time-dependent pressure ripple
p_i	Amplitude of i-th harmonic of pressure ripple
Q	Fourier transform of flow ripple
$q(t)$	Time-dependent flow ripple
q_i	Amplitude of i-th harmonic of flow ripple
R	Magnitude of harmonic component (pressure or flow ripple, as appropriate)
t	Time
ε_f	Error in calculation of flow ripple at junction
φ_i	Phase of i-th harmonic of pressure ripple
ν	Kinematic viscosity
θ	Phase of harmonic component (pressure or flow ripple, as appropriate)
ω	Frequency (rads per second)
ψ_i	Phase of i-th harmonic of flow ripple

5 Basic considerations

5.1 General

The time-dependent pressure and flow ripples in a hydraulic system can be described mathematically by a Fourier series. Figure 1 shows, as an example, a periodic flow ripple signal in the time domain, while Figure 2 shows the corresponding frequency domain representation. The phase can lie in the range –180° to 180°.

The spectra shown in Figure 2 present the harmonic components in terms of their amplitude and phase. It is also possible to present these components in terms of their real and imaginary parts. Frequency domain representations are readily obtained using frequency analysis instrumentation.

For the determination of the fluid-borne noise characteristics of hydraulic components and systems, only periodic signals are considered.

5.2 Frequency spectrum representation of pressure ripple

The time-dependent pressure ripple $p(t)$ is closely approximated by a finite sum of pure sinusoidal pressure ripples, $p_i(t)$. Each sinusoidal component is described by its amplitude (p_i) and phase (φ_i).

$$p(t) = \sum_{i=1}^{n} p_i \sin\left(2i\pi f_0 t + \varphi_i\right) \tag{1}$$

The time-dependent flow ripple $q(t)$ is also closely approximated by a finite sum of pure sinusoidal flow ripple, $q_i(t)$. Each sinusoidal component is described by its amplitude (q_i) and phase (ψ_i).

$$q(t) = \sum_{i=1}^{n} q_i \sin\left(2i\pi f_0 t + \psi_i\right) \tag{2}$$

At a particular frequency (f) which is an integer (m) multiple of the fundamental frequency (f_0) (i.e. $f = mf_0$), the pressure ripple has an amplitude P_m and phase φ_m. The corresponding flow ripple has an amplitude of Q_m and a phase of ψ_m.

It is also possible to represent these harmonic components in terms of their real and imaginary parts:

$$R\angle\theta = R\cos\theta + \mathrm{j}R\sin\theta \tag{3}$$

5.3 Mathematical modelling of wave propagation in a pipe in the frequency domain

The mathematical modelling of plane wave propagation presented in this part of ISO 15086 takes into account fluid viscosity effects and is readily applicable to analysis in the frequency domain. This model is appropriate for all Newtonian hydraulic fluids over a wide range of mean pressures and temperatures.

At each frequency, the flow ripple at one location (i) in a pipe is represented by a linear combination of the pressure ripple at that location and one other location (j). In complex number notation:

$$Q_{i\to j} = AP_i + BP_j \tag{4}$$

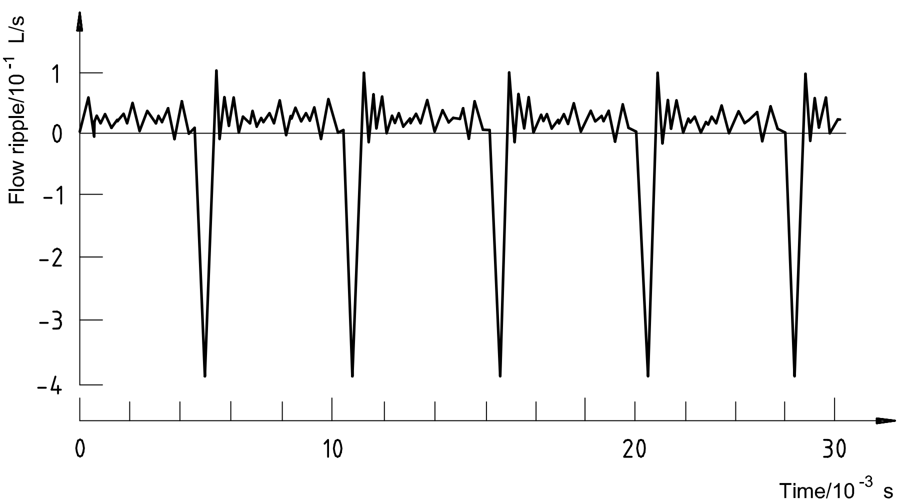
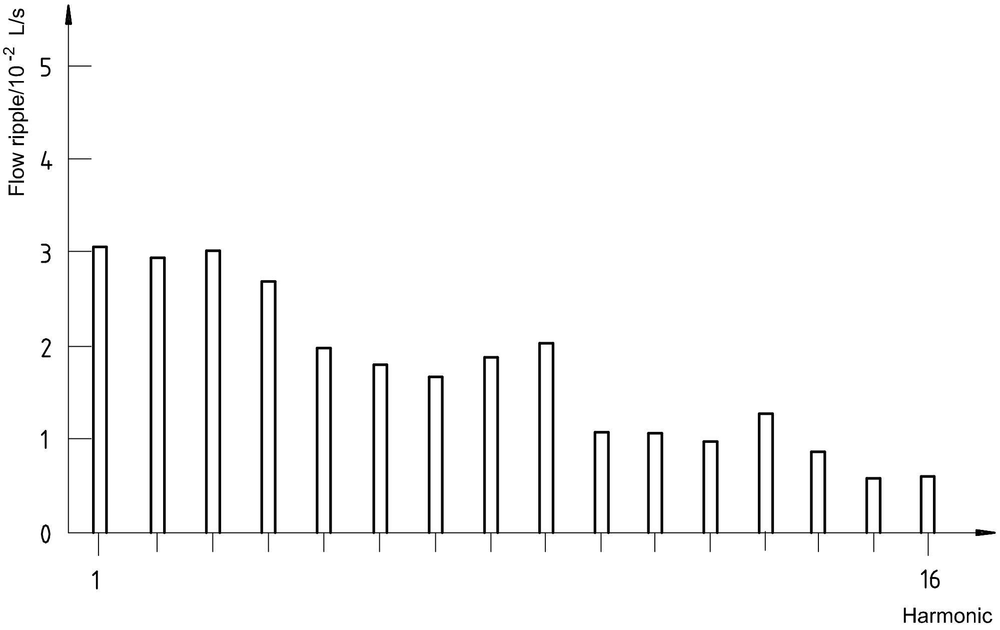
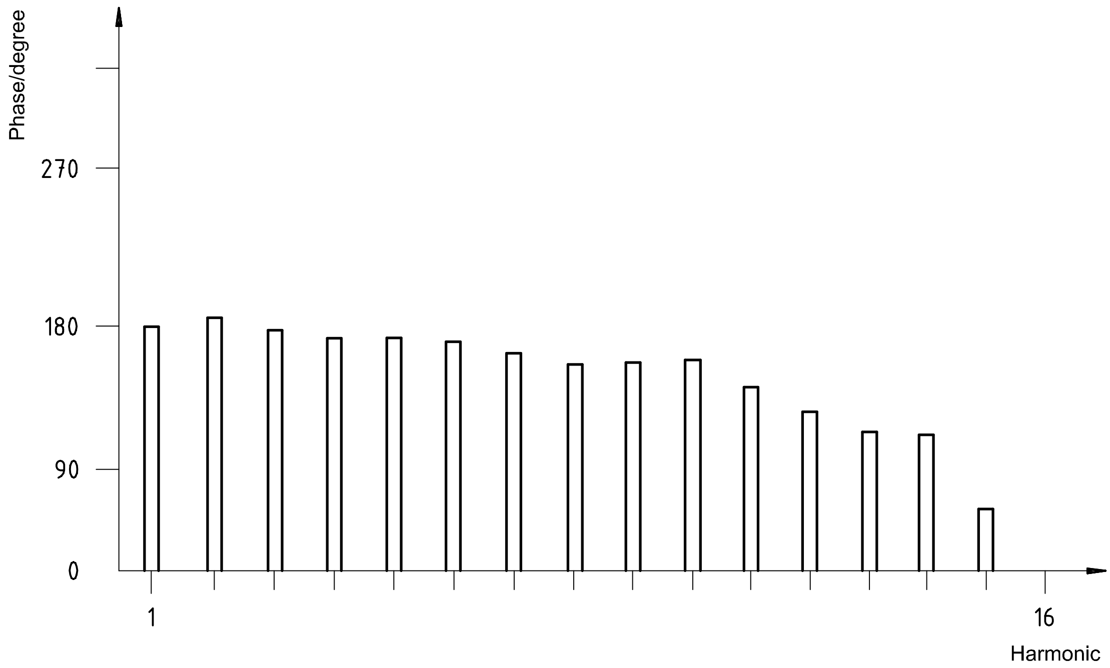


Figure 1 — Example of time domain waveform



a) Amplitude spectrum



b) Phase spectrum

Figure 2 — Frequency spectra corresponding to Figure 1

The volumetric flow pulsation $Q_{i \to j}$ is positive for flows from i to j. The complex numbers A and B are functions of frequency and depend on the geometric characteristics of the pipe and the characteristics of the fluid. With the effects of fluid viscosity at the pipe wall taken into account, a and b are closely approximated by:

$$A = \frac{\pi d^2}{4\rho c^2} \frac{\omega L}{a - jb} \coth\left[j(a - jb) \right] \tag{5}$$

$$B = \frac{\pi d^2}{4\rho c^2} \frac{\omega L}{a - jb} \frac{j}{\sin(a - jb)} \tag{6}$$

$$a = \frac{L}{c} \left(\omega + \sqrt{\frac{2\omega \nu}{d^2}} \right) \tag{7}$$

$$b = \frac{L}{c} \left(\frac{4\nu}{d^2} + \sqrt{\frac{2\omega \nu}{d^2}} \right) \tag{8}$$

The parameters a and b are calculated with sufficient accuracy provided:

$$\omega \gg \frac{4\nu}{d^2}$$

For example, $\nu = 50 \times 10^{-6}$ m^2/s (50 cSt) and d = 0,01 m. For the theory to be valid ω has to be much greater than 2 rad/s. This is the case for all hydraulic fluid power systems.

Because a pipeline of constant cross-sectional area has physical symmetry, the flow ripple at section (j) can be expressed by:

$$Q_{j \to i} = AP_j + BP_i \tag{9}$$

The complex numbers A and B are identical to the numbers in Equation 4.

5.4 Continuity equation

At the connecting point between two or more pipes, or between a pipe and a component, the algebraic sum of the flow equates to zero.

One consequence of this is that a single pipe can be subdivided into two separate pipes of the same cross-sectional area. The pressure ripple at the junction can then be expressed as a function of the pressure ripple at one location upstream of the junction and one location downstream of the junction. Consider the following:

$$Q_{2 \to 1} = AP_2 + BP_1 \tag{10}$$

$$Q_{2 \to 3} = A'P_2 + B'P_3 \tag{11}$$

A' and B' will differ from A and B if the distance between locations 2 and 3 is different from the distance between locations 1 and 2.

$$Q_{2 \to 1} + Q_{2 \to 3} = 0 \tag{12}$$

So

$$P_2 = -\frac{B}{A + A'} P_1 - \frac{B'}{A + A'} P_3 \tag{13}$$

This can be readily extended to cover the case of the junction of two pipes of different cross-sectional area.

From knowledge of the pressure ripple at two chosen locations, it is possible to evaluate the pressure ripple at another location either upstream or downstream. Consider the following example where the pressure ripple is measured at locations 1 and 2 and then used to infer the pressure ripple at location 3, downstream of locations 1 and 2:

$$Q_{3\to 1} = A^* P_3 + B^* P_1 \tag{14}$$

$$Q_{3\to 2} = A' P_3 + B' P_2 \tag{15}$$

and

$$Q_{3\to 1} = Q_{3\to 2} \tag{16}$$

So

$$P_3 = \left(\frac{B'}{A^* - A'}\right) P_2 - \left(\frac{B^*}{A^* - A'}\right) P_1 \tag{17}$$

where A' and B' relate to the pipe properties between locations 2 and 3 and A^* and B^* relate to the pipe properties between locations 1 and 3.

5.5 Sources of pressure and flow ripple

An ideal source comprises a device that creates pressure (or flow) ripple at the required amplitude and phase at a particular location in a hydraulic circuit. A practical source is likely to comprise a hydraulic device with an ideal source internally that is connected to an outlet port through an internal fluid passageway or passageways. This device transmits, with a particular frequency spectrum, a pressure (or flow) ripple of the source to the outlet port. The pressure (or flow) ripple at the port generally depends on the nature of the ideal source, the device construction, and the characteristics of the circuit to which it is connected.

5.6 Impedance

For fluid-borne noise characteristics of hydraulic components and systems, the impedance is related to the algebraic sum of the volumetric flows passing into the component or system. Flow into a component or system is taken to be positive.

Under steady-state conditions, the ratio of the pressure ripple to flow ripple at each harmonic frequency defines the impedance at that frequency. The impedance is expressed in terms of amplitude and phase, or, alternatively, by its real and imaginary parts.

5.7 Passive components and hydraulic noise generators

It is essential to differentiate between passive and other hydraulic components. Passive components have no significant source of energy internally. Any component with one or more internal energy sources is considered to be a combination of a passive component and a hydraulic noise generator.

6 Practical aspects

6.1 Pressure ripple measurement

It is possible to measure pressure ripple in hydraulic components and systems using a wide range of devices. The essential requirement is that the bandwidth of the device be appropriate to the range of frequencies of interest. Piezoelectric pressure transducers are particularly well suited to the measurement of pressure ripple in hydraulic circuits.

6.2 Flow ripple measurement

At present, no suitable devices are available for the direct measurement of flow ripple over an appropriate range of frequencies and operating conditions. As a consequence, it is normal practice to infer flow ripple from two (or more) pressure ripple measurements. For a rigid pipeline with known geometrical characteristics, the flow ripple can be inferred from two pressure ripple measurements using Equation 4. The complex number coefficients A and B can be evaluated using Equations 5 and 6, and a knowledge of the fluid properties and pipe geometry.

The flow ripple $Q_{1\to 2}$, just ahead of pressure transducer P_1, can be calculated from Equation 9 from a knowledge of the pressure ripples $P_i = P_1$ and $P_j = P_2$.

In order to estimate the pressure ripple and flow ripple at any location in a pipe, first the pressure pulsations should be calculated using Equation 13 or Equation 17 and then the flow ripple using Equation 4.

6.3 Local impedance measurement

The local impedance is defined by the ratio P/Q, where P and Q are specified at the same location. Using the technique described in 6.2, the impedance is readily calculated from the inferred or measured pressure ripple and the inferred flow ripple at the location of interest.

6.4 Speed of sound measurement

For cases where the speed of sound in the fluid enclosed by the pipe is not known, it is possible to infer the speed of sound from pressure ripple measurements at three distinct locations in a pipe.

The flow ripple at the location of the inner transducer can be obtained in two different ways. Equation 10 can be applied to determine the flow ripple using pressure ripple measurements P_1 and P_2, or Equation 11 can be applied using pressure ripple measurements P_2 and P_3. Because of flow continuity at the middle pressure transducer, the algebraic sum of the two flow ripples $Q_{2\to 1}$ and $Q_{2\to 3}$ should be zero. However, if there is an error in the speed of sound used in the calculations, the algebraic sum will be non-zero.

$$\varepsilon_{\mathrm{f}} = Q_{2\to 1} + Q_{2\to 3}$$

The speed of sound can be evaluated by choosing the best value that minimizes the sum of the moduli of the errors ε_{f} occurring at each of the harmonic frequencies measured. For the techniques described in this part of ISO 15086 to be valid, the mean velocity of the fluid in the pipe must be less than 1 % of the speed of sound. For hydraulic mineral oils this typically means mean velocities of less then 10 m/s.

It is important to note that the speed of sound obtained by this method relates to the specific case of the particular fluid used and the particular pipe used. For hydro-acoustic calculations it is essential to use speed of sound in the fluid enclosed in a real pipe rather than the speed of sound in the fluid enclosed in by a perfectly rigid container.

6.5 Matrix coefficient measurements

The hydro-acoustic characteristics of components can be represented using matrix notation. To illustrate this it is useful to consider the case of a single length of pipe that can be treated as a very simple two-port component with the particular characteristic of port-to-port symmetry (in general, however, this will not be the case). For symmetrical components, the relationship between pressure ripples and flow ripples at the two ports is represented as follows:

$$Q_{1\to 2} = AP_1 + BP_2 \tag{18}$$

$$Q_{2\to 1} = AP_2 + BP_1 \tag{19}$$

which can be represented in matrix form as

$$\begin{bmatrix} Q_{1\to2} \\ Q_{2\to1} \end{bmatrix} = \begin{bmatrix} A & B \\ B & A \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \tag{20}$$

The hydro-acoustic properties of a wide range of components can be described in this manner. For cases with port-to-port symmetry it is possible to undertake measurements that allow the matrix coefficients to be calculated. In general the coefficients will be complex. In order to determine the coefficients it is necessary to know P_1, P_2, $Q_{1\to2}$ and $Q_{2\to1}$. The coefficients A and B can then be obtained as follows:

$$A = \frac{\dfrac{Q_{1\to2}}{P_2} - \dfrac{Q_{2\to1}}{P_1}}{\dfrac{P_1}{P_2} - \dfrac{P_2}{P_1}} \tag{21}$$

$$B = \frac{\dfrac{Q_{1\to2}}{P_1} - \dfrac{Q_{2\to1}}{P_2}}{\dfrac{P_2}{P_1} - \dfrac{P_1}{P_2}} \tag{22}$$

These coefficients are readily calculated as a function of frequency using appropriate computer algorithms.

For asymmetrical components, the situation is more complex and three coefficients are required to describe the characteristics of the component. The relevant equations are:

$$Q_{1\to2} = A'P_1 + B'P_2 \tag{23}$$

$$Q_{2\to1} = C'P_2 + B'P_1 \tag{24}$$

The matrix representation is:

$$\begin{bmatrix} Q_{1\to2} \\ Q_{2\to1} \end{bmatrix} = \begin{bmatrix} A' & B' \\ B' & C' \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} \tag{25}$$

The method of evaluating coefficients in this case is more complex than for the symmetrical case and is dealt with in another part of ISO 15086.

6.6 Measurement of hydraulic noise generator characteristics

A hydraulic noise generator is a component with one or more hydro-acoustic energy sources. For example, positive displacement pumps and motors generate hydro-acoustic energy at a series of distinct frequencies. These frequencies are integer multiples of the rotating shaft frequency. At frequencies other than those produced by the generator, the internal energy source can be treated as quiescent. As a consequence, the generator can be treated as a passive component at these frequencies and hence can be characterized by its transfer matrix coefficients.

In order to completely characterize the hydraulic noise generator, it is necessary to define both the behaviour of the internal energy source and the transfer matrix coefficients representing the passive aspects of the component. Techniques for characterizing such generators are described in other parts of ISO 15086.

6.7 Measurement errors

There are two common measurement errors that can arise in hydro-acoustic investigations.

a) One common measurement error is a consequence of the variation in signals between successive frequency spectrum evaluations. It is essential to average a large number of spectra in order to average out the effects of broad band noise. Each individual spectrum should be synchronized to the same time datum or to a datum associated with the fundamental frequency of the noise generator.

b) The other common measurement error is a consequence of the presence of a hydro-acoustic energy generator inside a component being treated as passive. Even if the energy levels are low, these sources can introduce significant measurement errors. Considerable care should be taken to avoid this problem, which may be frequently encountered in hydraulic circuits. High fluid velocities within a component are one possible cause of broad-band noise, and appropriate steps should be taken to identify this.

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