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BRITISH STANDARD

BS EN 60994:1993
IEC 994:1991

Guide for field measurement of vibrations and pulsations in hydraulic machines (turbines, storage pumps and pump-turbines)

The European Standard EN 60994:1992 has the status of a British Standard

UDC 534.6:534.83:621.22:621.65

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This British Standard, having been prepared under the direction of the Machinery and Components Standards Policy Committee, was published under the authority of the Standards Board and comes into effect on 15 February 1993

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National foreword

This British Standard has been prepared under the direction of the Machinery and Components Standards Policy Committee and is the English language version of EN 60994:1993 *Guide for field measurement of vibrations and pulsations in hydraulic machines (turbines, storage pumps and pump-turbines),* published by the European Committee for Electrotechnical Standardization (CENELEC). It is identical with IEC 994:1991 published by the International Electrotechnical Commission (IEC).

For graphical, symbols, and letter symbols and signs approved by the IEC for general use, readers are referred to:

— IEC Publication 27: *Letter symbols to be used in electrical technology;*

— IEC Publication 617: *Graphical symbols for diagrams.*

The symbols and signs contained in the present publication have either been taken from IEC Publications 27 or 617, or have been specifically approved for the purpose of this publication.

For general terminology, readers are referred to IEC Publication 50: *International Electrotechnical Vocabulary (IEV),* which is issued in the form of separate chapters each dealing with a specific field, the General Index being published as a separate booklet. Full details of the IEV will be supplied on request.

The terms and definitions contained in the present publication have either been taken from the IEV or have been specifically approved for the purpose of this publication.

Some Sections and Parts of BS 4727 are identical with or technically equivalent to IEC Publication 50. All Parts of BS 3939, except for Part 1, are identical with IEC Publication 617.

Additional information. ISO 2041 referred to in the text was the 1975 edition of the standard. This edition has now been superseded by ISO 2041:1990. BS 3015:1991 is identical with ISO 2041:1990.

In **2.2**, paragraph 1, line 2 and **10.2**, line 3, reference is made to "IEC Publication 000". This publication has now been published as IEC 41:1991 and it is envisaged that, if it is accepted as a European Standard, it will be published in the BS EN series.

EN 60994 was produced as a result of international discussion in which the United Kingdom took an active part.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the EN title page, pages 2 to 60, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 60994

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Descriptors: Hydraulic machine, turbine, pump, measuring, vibration, test, test conditions

English version

Guide for field measurement of vibrations and pulsations in hydraulic machines (turbines, storage pumps and pump-turbines)

(IEC 994:1991)

Guide pour la mesure in situ des vibrations et fluctuations sur machines hydrauliques (turbines, pompes d'accumulation et pompes-turbines)
(CEI 994:1991)

Leitfaden für die Messung von Schwingungen und Druckpulsationen an hydraulischen Maschinen (Turbinen, Speicherpumpen und Pumpturbinen) in Kraftwerken
(IEC 994:1991)

This European Standard was approved by CENELEC on 1992-09-15. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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Foreword

The CENELEC questionnaire procedure, performed for finding out whether or not the International Standard IEC 994:1991 could be accepted without textual changes, has shown that no common modifications were necessary for the acceptance as European Standard.

The reference document was submitted to the CENELEC members for formal vote and was approved by CENELEC as EN 60994 on 15 September 1992.

The following dates were fixed:

— latest date of publication of an identical national standard	(dop) 1993-09-01
— latest date of withdrawal of conflicting national standards	(dow) 1993-09-01

Annexes designated "normative" are part of the body of the standard. In this standard, Annex ZA is normative.

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Introduction

On a machine in service, pulsations and vibrations which cannot be avoided and which do not affect by themselves the service life of the plant where they occur, can always be observed. Their values depend on many factors, among which are the flow pattern in the water passages under different operating conditions of the unit, peculiarities of the design as well as the thoroughness of manufacture, erection and maintenance. Such pulsations and vibrations can be considered as detrimental only when certain parts of the machine or of the plant are subject to forces that may impair its resistance or when unacceptable disturbances are carried to its environment.

In extreme cases, vibrations in hydraulic machines can result in the formation of cracks and even in fracture of components due to fatigue[1].

Excessive vibration in hydraulic machines not only can reduce their trouble-free service life but can also affect operation of governing systems and instruments, the behaviour of the attached structures and the health of personnel.

Measurement of pulsation and vibration characteristics or, preferably, of their effects is to be carried out in accordance with this guide which also gives the information necessary to derive the value of the physical quantities from the readings of the measuring instruments.

Given the present state of knowledge, it can only be hoped that measurements made in compliance with this guide will reveal a basic characteristic making it possible to relate pulsations and vibrations to their effects statistically, with an acceptable confidence level.

Vibration studies of a hydraulic machine represent a long and difficult operation and hence are expensive (particularly as regards the non-availability of the machine) and therefore should be undertaken only if a limited number of measurements of stresses or movements indicates the possibility of a real danger. The purpose of such work is, if possible, to eliminate the source of detrimental loadings after having identified it or, should this not be practicable, to define an operating procedure reducing such loadings to an acceptable level. There are many sources of disturbances but a very small number of them, and even one only, may create a real problem on a given machine.

As a rule, the vibrational state of a hydraulic machine is assessed from tests in which the vibration is measured at individual characteristic points of the structure. A standard experimental set-up, designed on the basis of good practice and experience, should already yield sufficient indications about the general vibrational conditions of the machine. However, examination of results thus acquired can sometimes point to strong local amplification (resonance) in some vital parts of the machine; if such is the case, the affected part(s) should be more closely investigated by means of an appropriate experimental arrangement. Flow pattern in the water passages may have important effects on the vibrations of hydraulic machines. In order to obtain an accurate vibration analysis, it is common practice to relate appropriately located measurements of vibrations (see **5.2.1** and **5.2.2**) with appropriately located measurements of pulsations[2] of other important quantities, such as:

- — pressure pulsations (see **5.2.3**);
- — pulsations of local strains and corresponding stresses (see **5.2.4**);
- — shaft torque pulsations (see **5.2.5**);
- — rotation speed pulsation (see **5.2.6**);
- — power pulsations (see **5.2.7**);
- — guide vane torque pulsations (see **5.2.8**);
- — radial thrust pulsations measured at guide bearings (see **5.2.9**);
- — axial thrust pulsations measured at thrust bearing (see **5.2.10**);

and, if need be, also other quantities.

It is in no way intended that all the measurements listed in this guide should be carried out in every case.

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[1] In previous years fatigue failures in hydraulic machines were few in number. However, the current tendency to increase specific loads and to save material in the design of hydraulic machines can lead to lowering of dynamic rigidity of the structure, which may increase the risk of vibration in newly designed machines. Also the increase in geometrical dimensions stemming from increasing unit capacity can lead to a lowering of characteristic vibration frequencies of the machine or of some parts thereof (guide vanes, etc.). Thus the frequencies in question could more easily interact with the frequencies of hydraulic and/or electrical oscillations in the system (or harmonics thereof).

[2] In this guide, the term “pulsation” is understood to mean any periodic (or quasi-periodic) fluctuation, irrespective of its frequency.

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Section 1. General

1 Scope and object

1.1 Scope

1.1.1 This guide applies to any type of reaction or impulse turbine, as well to any type of pump-turbine and storage pump, coupled to an electric generator or motor.

1.1.2 The guide covers the field of vibration and pulsation tests referred to as standard tests.

The objectives of the tests are as follows:

- — Assessment of hydraulic machine design, manufacture and quality of erection from the viewpoint of vibration[3].
- — Assessment of the changes of vibration behaviour during the machine life.
- — Provision of recommendations applying to operation of unit (for instance, choice of the most appropriate transient sequences).
- — Aid in analysing faults and break downs.

1.1.3 If it is not possible to apply the recommendations of the guide because of the construction of the hydraulic machine, or if it is not necessary to conduct some of the measurements, such items may be omitted on prior agreement between the manufacturer and the user.

1.2 Object

1.2.1 To establish uniform rules to be applied when carrying out vibration and pulsation tests. To establish methods of measuring and of test data processing.

1.2.2 To indicate criteria for a unified approach to the comparison of vibrations and pulsations of different hydraulic machines of the same class (see **2.4**).

1.2.3 To ensure the possibility of accumulating actual data of sufficient homogeneity on different hydraulic machines.

1.3 Excluded topics

1.3.1 The guide excludes all matters of purely commercial interest.

1.3.2 The guide is not concerned with special vibration and pulsation tests for research purposes, although it is recommended that the methods described in the guide be applied to usual vibration and pulsation tests.

1.3.3 Laboratory model vibration and pulsation tests and tests of separate full-sized parts in the workshop are not dealt with in this guide.

However, if pulsation tests on a model are available, they should be taken into consideration.

1.3.4 The problems related to the vibrations of civil engineering works and of parts of the electrical machine other than bearing(s) or the shaft, as well as the pressure pulsations in the waterways external to the machine[4], are not dealt with in the guide.

However, in specific cases, when the causes of excessive vibration of a hydraulic machine are uncertain or might be influencing other parts of the plant, it may be appropriate to inspect the civil engineering work structures and/or the electrical machine as well as the waterways external to the machine.

1.3.5 The guide excludes recommendations on identifying and eliminating causes of vibrations.

1.3.6 Although quite often noise measurements and noise analysis, if adequately performed, can be a useful diagnostic tool to assess vibratory troubles of a hydraulic machine, this guide considers only mechanical vibrations to the exclusion of acoustical effects (noise).

1.3.7 Regulation systems may interact with phenomena of "pulsations" of hydraulic, mechanical and electrical quantities in a hydroelectric power plant. However, treatment of such interactions or guidelines for conducting artificial-excitation test by injecting a sine signal in the governor loop (as is often done e.g. to determine the frequency response of the system) are outside the scope of this guide.

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[3] Recommendations on assessment of the vibrational and pulsatory state of the machine will not be prepared until systematic data have been accumulated in accordance with this guide and have been properly interpreted.

[4] In the case of absence of valves and/or gates, the machine is understood to include waterways between high pressure/low pressure reference sections, as specified for guarantees [see IEC Publication 000 (see footnote 5 on page 7)].

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2 Terms, definitions, symbols and units

2.1 Units

The International System (SI) is used throughout this guide.

2.2 Terms

The terms, definitions and symbols relating to hydraulic turbines, storage pumps and pump-turbines are in compliance with the IEC Publication 000[5]. The terms not defined in **2.3** can be found in the publication just mentioned.

The terms, definitions and symbols relating to vibrations and pulsations as well as mathematical terms are in compliance with ISO Standard 2041 and IEC Publications 184 and 222.

2.3 List of terms specific to this guide

Tabulated below are the terms, symbols and units relating to vibrations and pulsations adopted throughout this guide.

	Terms	Definitions	Symbols	Units
2.3.1	**Terms relating to description of vibrations and pulsations as functions of time**[a]			
2.3.1.1	**Dynamic absolute displacement**	(see IEC 184)	$u\ (t)$	m
2.3.1.2	**Dynamic absolute velocity**	(see IEC 184)	$v\ (t)$	m/s
2.3.1.3	**Dynamic absolute acceleration**	(see IEC 184)	$w\ (t)$	m/s^2
2.3.1.4	**Dynamic relative displacement between two parts e.g. the shaft and the part on which the proximity transducer is fixed (d = 0 when the shaft touches the transducer)**		$d\ (t)$	m
2.3.1.5	**Pressure pulsation**	Oscillatory variation of the pressure of the liquid referred to its mean value during a time interval Δt previously selected	$\tilde{p}\ (t)$	Pa
2.3.1.6	**Strain pulsation**	Oscillatory variation of the strain referred to its mean value during a time interval Δt previously selected	$\tilde{\varepsilon}\ (t)$	m/m
2.3.1.7	**Stress pulsation**	Oscillatory variation of the stress referred to its mean value during a time interval Δt previously selected	$\tilde{\sigma}\ (t)$	N/m^2
2.3.1.8	**Shaft torque pulsation**	Oscillatory variation of the shaft torque referred to its mean value during a time interval Δt previously selected	$\tilde{M}\ (t)$	N · m
2.3.1.9	**Rotational speed pulsation**	Oscillatory variation of the rotational speed referred to its mean value during a time interval Δt previously selected	$\tilde{n}\ (t)$	rev/s

[a] For the definitions of vibrations and pulsations see **2.3.2**.

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[5] At present Document 4(Central Office)48.

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	Terms	Definitions	Symbols	Units
2.3.1.10	**Power pulsation**	Oscillatory variation of the power referred to its mean value during a time interval Δt previously selected	$\tilde{P}(t)$	W
2.3.1.11	**Guide vane torque pulsation**	Oscillatory variation of the guide vane torque referred to its mean value during a time interval Δt previously selected	$\tilde{M}_{\mathrm{GV}}(t)$	N · m
2.3.1.12	**Radial pulsation measured at guide bearing**	Oscillatory variation of the radial load on the guide bearing referred to its mean value during a time interval Δt previously selected	$\tilde{R}(t)$	N
2.3.1.13	**Axial pulsation measured at thrust bearing**	Oscillatory variation of the axial load on the thrust bearing referred to its mean value during a time interval Δt previously selected	$\tilde{T}(t)$	N
2.3.2	**General terms relating to parameters used to describe vibrations and pulsations**[a]			
2.3.2.1	**Vibration**	The variation with time of a quantity, which is descriptive of the motion or position of a mechanical system, when the magnitude is alternately greater and smaller than some average value of reference		
2.3.2.2	**Periodic vibration or pulsation**	A quantity whose values recur at equal intervals of the independent variable (time) NOTE A periodic quantity $X(t)$ which is a function of time t, and can be expressed as $X = f(t) = f(t + nT)$ where n is an integer, T is a constant interval of time and t is the running time		
2.3.2.3	**Fundamental period (period)**	The smallest interval of time for which a periodic function of time repeats itself (see **2.3.2.2**) NOTE If there is no ambiguity, the fundamental period is called the period	T	s
2.3.2.4	**Frequency**	The reciprocal of period	f	Hz
2.3.2.5	**Harmonic (of a periodic quantity)**	A sinusoidal component (of a composite periodic function of time) whose frequency is an integer multiple of the fundamental frequency		
2.3.2.6	**Angular frequency (circular frequency)**	The product of the frequency of a sinusoidal phenomenon by the factor 2π	ω	rad/s

[a] The definition of "pulsation" is the same as that of "vibration", with the difference that the quantity involved is not descriptive of the motion or position of a mechanical system.

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	Terms	Definitions	Symbols	Units
2.3.2.7	**Simple harmonic quantity; sinusoidal quantity**	A periodic quantity that is a sinusoidal function of time. Thus $X = A \sin (\omega t + \varphi)$ where $X(t)$ is the simple harmonic quantity. A is the amplitude, ω is the angular frequency (see **2.3.2.6**), t is the running time, φ is the phase angle of the oscillation (radians)		
2.3.2.8	**Simple harmonic motion or pulsation**	A motion or pulsation that is a sinusoidal function of time		
2.3.2.9	**Phase angle; Phase (of a sinusoidal quantity)**	If a sinusoidal quantity has advanced through mT units of time (T being the period) as measured from a value of time taken as reference, the phase angle is $m2\pi$	φ	rad
2.3.2.10	**Amplitude**	The maximum value of a sinusoidal quantity $X(t)$	A	[X] (different units according to the physical nature of X)
2.3.2.11	**Peak-to-peak value of an oscillating quantity**[a]	The algebraic difference between the extreme values of the quantity. In the case of a sinusoidal quantity the peak-to-peak value is twice the amplitude, i.e. $2A$	ΔX_{pp}	[X]
2.3.2.12	**Compound vibration or pulsation**	Vibration or pulsation consisting of the super-position (sum) of several simple harmonic vibrations or pulsations NOTE In cases when the ratio of each of the frequencies of simple harmonic vibrations to fundamental frequency is an integer, compound vibration is called polyharmonic vibration		
2.3.2.13	**Resonance**	Resonance of a system in forced oscillation exists when any change, however small, in the frequency of excitation causes a decrease in the response of the system		
2.3.2.14	**Random vibration or pulsation**	A vibration or pulsation, of which the magnitude cannot be precisely predicted for any given instant of time		

[a] Peak value (ΔX_p[X]) of an oscillating quantity (as opposed to peak-to-peak value) is the maximum absolute value of the deviation from the mean value (see **2.3.3.1**) of the oscillating quantity.

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	Terms	Definitions	Symbols	Units
2.3.3	**Mathematical terms**			
2.3.3.1	**Average value; mean value; algebraic mean value**	a) The average value of a number of homogeneous discrete quantities is equal to the algebraic sum of the quantities divided by the number of quantities. The average value is equal to: $\overline{X} = \frac{\sum_{n=1}^{N} X_n}{N}$ where X_n is the value of nth quantity: N is the total number of discrete quantities b) The average value of a continuous function, $X(t)$, over a time interval between t_1 and t_2 is equal to: $\overline{X} = \frac{\int_{t_1}^{t_2} X(t)\,\mathrm{d}t}{t_2 - t_1}$	$\overline{X}$	[X]
2.3.3.2	**Standard deviation effective value referred to the mean**	The root-mean-square (r.m.s.) value of the deviation of a set of numbers (or a function) from the mean value a) For a set of numbers X_1, X_2, ... X_N $\overline{X}_{\mathrm{eff}} = \sqrt{\frac{\sum_{n=1}^{N} (X_n - \overline{X})^2}{N}}$ where the subscript n refers to the n-th value. N is the total number of discrete quantities in the set, $\overline{X}$ is the mean value of the set (see **2.3.3.1**)[a] b) If the quantity $X(t)$ is a continuous function of t, its effective value over an interval between t_1 and t_2 is: $\overline{X}_{\mathrm{eff}} = \sqrt{\frac{\int_{t_1}^{t_2} [X(t) - \overline{X}]^2\,\mathrm{d}t}{t_2 - t_1}}$	$\overline{X}_{\mathrm{eff}}$	[X]
2.3.3.3	**Root-mean-square value: r.m.s. value (effective value)**	a) The root-mean-square (r.m.s.) value of a set of numbers is the square root of the average of their squared values. The r.m.s. value of the set of numbers can be represented as: $X_{\mathrm{rms}} = \sqrt{\frac{\sum_{n=1}^{N} X_n^2}{N}}$	X_{rms}	[X]

[a] Sometimes the standard deviation for the data of a sample is defined with ($N - 1$), replacing N in the denomination because the resulting value represents a better estimate of the standard deviation of a population from which the sample is taken. For larger values of N (i.e. $N > 30$) there is practically no difference.

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	Terms	Definitions	Symbols	Units
		where the subscript n refers to the n-th value and N is the total number of discrete homogeneous quantities b) The root-mean-square (r.m.s.) value of a continuous function, $X(t)$ over an interval between t_1 and t_2, is equal to the square root of the average of the squared values of the function over the interval. The r.m.s. value of a continuous single-valued function, $X(t)$ over an interval between t_1 and t_2 is: $$X_{\mathrm{rms}} = \sqrt{\frac{\int_{t_1}^{t_2} [X(t)]^2 \, \mathrm{d}t}{t_2 - t_1}}$$ NOTE In vibration theory the average or mean value of the vibration is equal to zero. In this case the r.m.s, value X_{rms} is equal to the standard deviation $\tilde{X}_{\mathrm{eff}}$ (see **2.3.3.2**) and the mean square value X^2_{rms} is equal to the variance $\tilde{X}^2_{\mathrm{eff}}$ (see **2.3.3.4**). In the case of a sinusoidal quantity of amplitude A its effective value is $A/\sqrt{2}$		
2.3.3.4	**Variance**	The square of the standard deviation NOTE When the mean value of a variable is zero, the variance is the mean square value of the variable (see Note 2 under Mean square value, **2.3.3.5**)	$\tilde{X}^2_{\mathrm{eff}}$	[X^2]
2.3.3.5	**Mean square value**	The mean square value of a function (or set of numbers) over a given interval is equal to the mean of the squared values of the function (or set of numbers) over that interval NOTE 1 The mean square value is the square of the r.m.s. value NOTE 2 When the mean value $\bar{X}$ is zero the mean square value is equal to the variance (see **2.3.3.4**) NOTE 3 If the mean value $\bar{X}$ is not zero then: $$X^2_{\mathrm{rms}} = \tilde{X}^2_{\mathrm{eff}} + \bar{X}^2$$	X^2_{rms}	[X^2]
2.3.4	**Other terms utilized**			
2.3.4.1	**Number of guide or diffuser vanes (reaction machines), or number of Pelton nozzles**		z_0	
2.3.4.2	**Number of runner impeller blades (reaction machines), or number of Pelton buckets**		z_2	
2.3.4.3	**Flow velocity**	The relative velocity of flow over a part to be investigated, at a point P, outside the thickness of the boundary layer, to be specified (see Figure 1)	v_{w}	m/s

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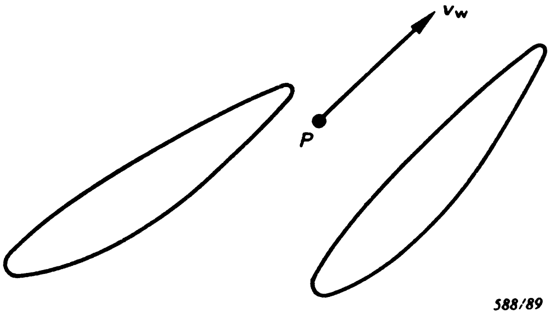

Figure 1 — Definition of flow velocity[a]

[a] These definitions are only a rough suggestion to evaluate the order of magnitude of frequency through the Strouhal number (see **6.1.1**).

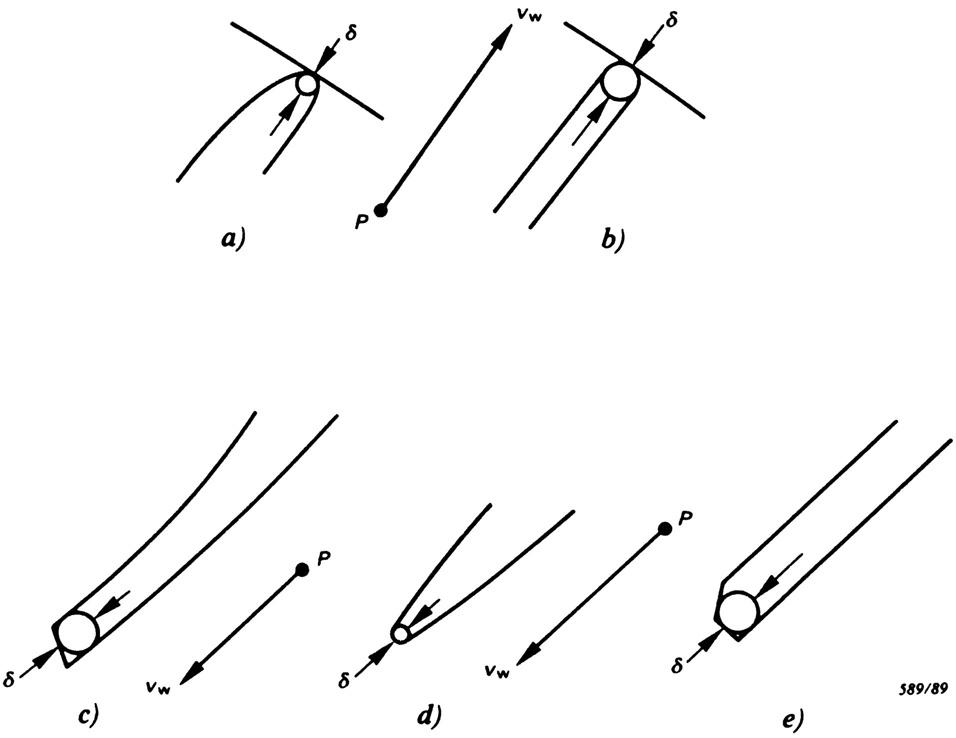

Figure 2 — Definition of thickness of trailing edge of a hydraulic profile[a]

[a] These definitions are only a rough suggestion to evaluate the order of magnitude of frequency through the Strouhal number (see **6.1.1**).

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	Terms	Definitions	Symbols	Units
2.3.4.4	**Thickness of trailing edge of a hydraulic profile (guide vane, runner blade, etc.)**	Maximum diameter of a sphere tangent to the two opposite surfaces of the profile near the trailing edge (see Figure 2)	δ	m
2.3.4.5	**Limit frequency (lower, upper)**	The lower and upper frequency values of the frequency range of the process under investigation	f_L, f_U	Hz
2.3.4.6	**Lower/upper limit frequency of measuring channel**	Actual lower/upper limit of frequency of measuring channel, where amplification is reduced by 3 dB with respect to the flat portion of the amplification versus frequency response curve	f_{Lr} f_{Ur}	Hz
2.3.4.7	**Power spectral density**	The power spectral density is the mean square value of that part of the quantity, passed by a narrow band filter of centre frequency f, per unit bandwidth in the limit as the bandwidth approaches zero and the averaging time approaches infinity	$G(f)$	$[X^2] \cdot s$ where [X] is the unit in which the oscillating quantity X is measured
2.3.4.8	**Constant relative (percentage) bandwidth of an analyzer**	The ratio $\beta = \frac{f_1 - f_2}{\sqrt{f_1 \cdot f_2}} \times 100$ where f_1, f_2 = frequency values at 3 dB drop points of the analyzer frequency response curve	β	%
2.3.4.9	**Upper cut-off frequency of pressure transducer installation**	Maximum frequency at which pressure transducer amplitude distortion caused by transducer installation (see Figure D.1) does not exceed 3 dB	f_c	Hz
2.3.4.10	**Volume of pressure transducer chamber (see Figure D)**	Volume of the chamber where the pressure transducer is mounted	V_c	m^3
2.3.4.11	**Cross-sectional area and length of the pressure transducer pipe (see Figure D)**	Cross-sectional area and length of the connecting pipe connecting the pressure transducer to the water passage of the hydraulic machine	A_c L_c	m^2 m
2.3.4.12	**Wave propagation velocity in pressure line**	Velocity of propagation of pressure waves in the pressure line (see **2.3.4.11**)	a_c	m/s
2.3.4.13	**Recording velocity**	Velocity of recording beam or pen movement with respect to the recording paper	v_s	m/s

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	Terms	Definitions	Symbols	Units
2.3.4.14	**Signal recording time**	Period of time during which a signal from a transducer is recorded	t_r	s
2.3.4.15	**Vibration component frequency**	Frequency of recorded component to be investigated	f_i	Hz
2.3.4.16	**Number of cycles recorded**	Number of component cycles to be recorded	N_r	
2.3.4.17	**Tape or paper speed**	Tape or paper speed during recording	v_r	m/s
NOTE Other terms and symbols, not listed here, are defined in the text as the necessity arises.				

2.4 Classification of hydraulic machines

Hydraulic machines are classified into their types on the basis of the future "Guide for the Nomenclature of Hydraulic Turbines, Storage Pumps and Pump-Turbines".

Designs of hydraulic machines and their parameters are highly different. To facilitate the comparison of vibrations and pulsations of different machines the various designs are subdivided into a number of different classes.

2.4.1 The following features are used as the basis for classification[6]:

— *Type of hydraulic machine*

Turbines: Pelton, inclined jet, cross flow, Francis, diagonal flow (Deriaz), propeller, Kaplan, bulb, rim-generator (straight-flow), S-type.

Pumps: centrifugal (single stage, multistage), diagonal flow, axial flow.

Pump turbines: Francis (single stage, multistage not regulated and regulated), diagonal flow, axial flow.

— *Arrangement of the shaft* (vertical, horizontal, inclined).

— *Number and position of bearings.*

— *Arrangement of the machines:* suspended type, umbrella type supported on the lower bearing bracket, umbrella type supported on the head cover, thrust bearing at lower end of the machine in relation to the position of the thrust bearing.

2.4.2 As a function of the arrangement of the shaft and of the number and position of bearings the following principal classes of hydraulic machines are formed (some examples of arrangements are shown in Figure 3).

2.4.2.1 The class of vertical machines includes:

— suspended machines (Figure 3a)

— umbrella type machines (Figure 3b and Figure 3c)

— machines with the thrust bearing at the lower end of the shaft (Figure 3d).

2.4.2.2 The class of horizontal machines includes:

— machines with two bearings (Figure 3e and Figure 3g)

— machines with three bearings

— machines with four bearings (Figure 3f).

2.4.3 The class of bulb machines includes:

— machines with cantilever arrangement of runner and generator (Figure 3h);

— machines with additional radial support located on an outlet stayring (Figure 3i).

Figure 3k gives an example of S-type machines.

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[6] This classification is not intended to be exhaustive, but to cover only the more widely used types: besides, the figures are intended only as indicative schemes for easy reference to the list of arrangements and parts on page 15.

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The general description of the figures and a list of the numbers used for the identification of the main parts within the arrangements is summarized in the following

Figure 3a: vertical suspended machine.
Figure 3b: vertical umbrella-type machine.
Figure 3c: vertical umbrella-type machine.
Figure 3d: vertical machine supported at the lower end shaft.
Figure 3e: horizontal machine with two bearings.
Figure 3f: horizontal machine with four bearings.
Figure 3g: pair of horizontal machines with two bearings.
Figure 3h: bulb machine with cantilever arrangement.
Figure 3i: bulb machine with additional radial bearing.
Figure 3k: S-type machine.

List of parts and reference numbers:

1 Runner/impeller.
2 Shaft.
3 Generator/motor.
4 Head cover.
5 Lower bearing bracket.
6 Upper bearing bracket.
7 Thrust bearing support.
8 Turbine (pump/pump-turbine) guide bearing.
9 Generator/motor guide bearing.
10 Thrust bearing.
11 Guide and thrust bearing combined.
12 Coupling.
13 Gear box.

Figure 3 — Some arrangements of hydraulic machines (See following pages)

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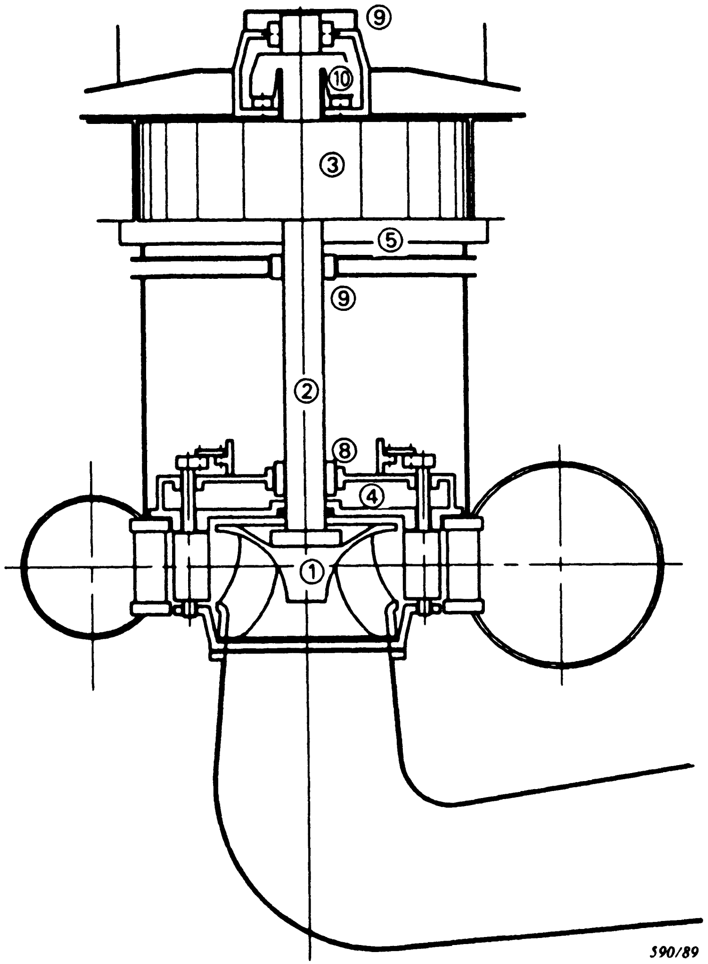

Figure 3a — Example of a vertical suspended machine (Francis turbine) with three guide bearings

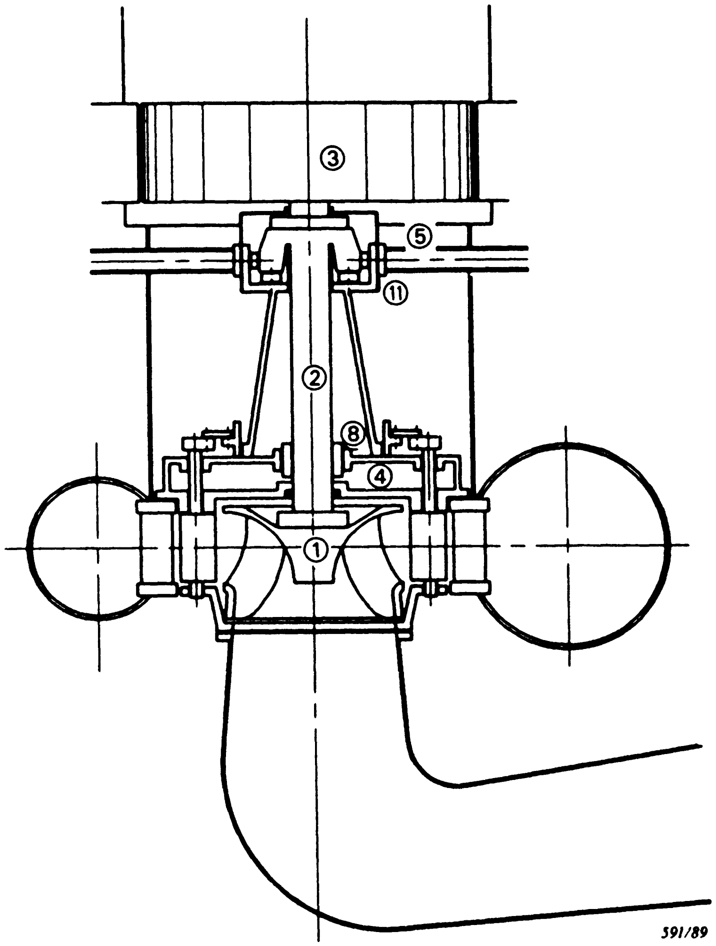

Figure 3b — Example of a vertical machine (Francis turbine) of umbrella type with the bearing on the turbine head cover and cantilever arrangement of the generator

(List of reference numbers, see general description of Figure 3, page 15)

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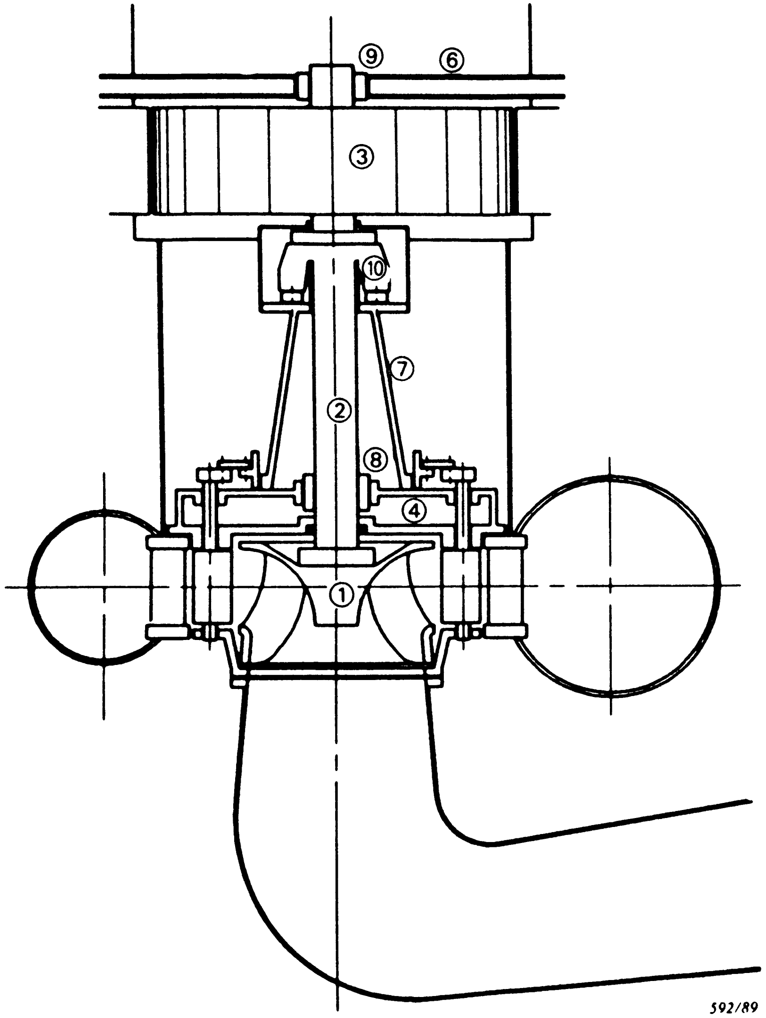

Figure 3c — Example of a vertical machine (Francis turbine) of umbrella-type with the thrust bearing on the head cover and two guide bearings

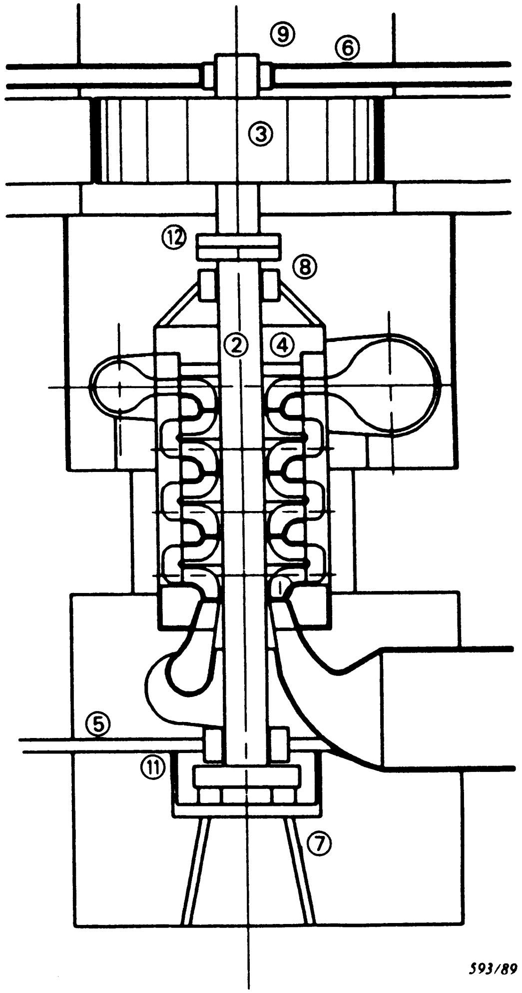

Figure 3d — Example of a vertical machine (four- stage storage pump) with the thrust bearing at the lower end of the shaft and three guide bearings

(List of reference numbers: see general description of Figure 3)

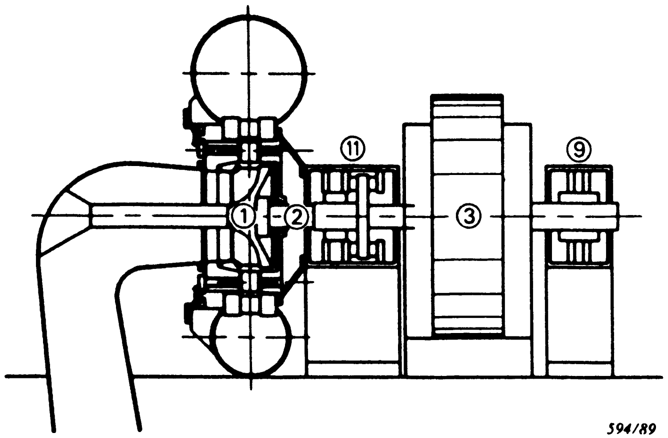

Figure 3e — Example of a horizontal machine (Francis turbine) with two bearings

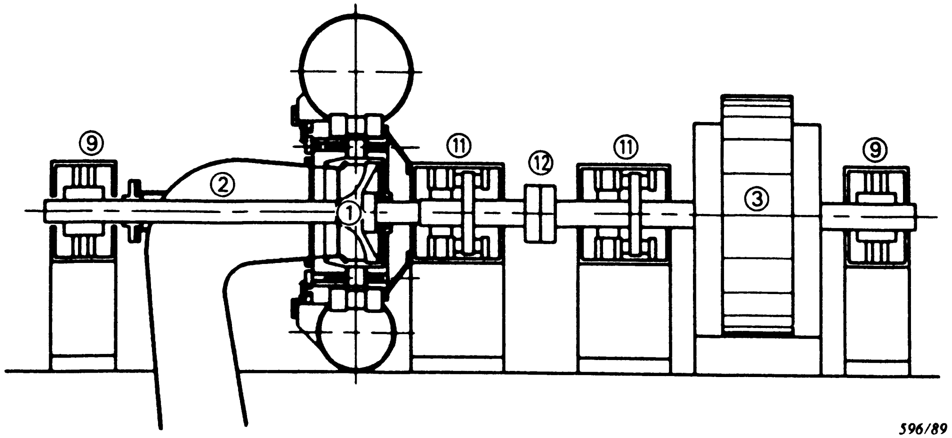

Figure 3f — Example of a horizontal machine (Francis turbine) with four bearings

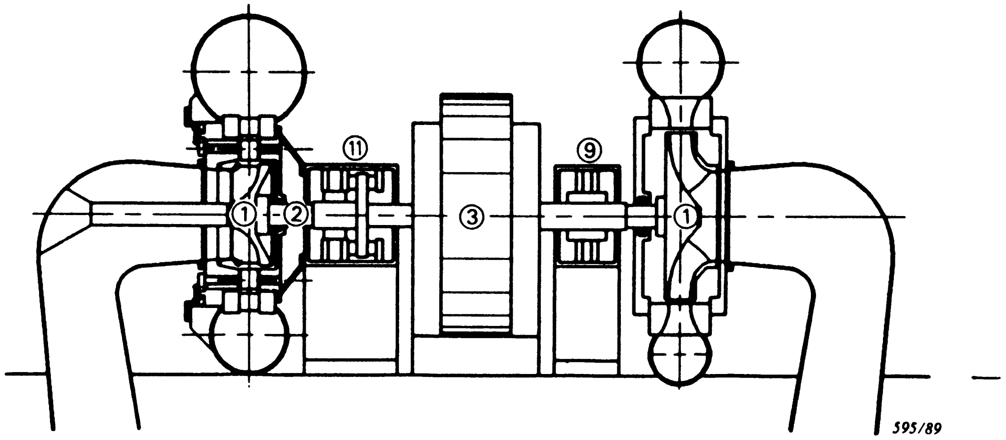

Figure 3g — Example of a horizontal machine with two bearings, a Francis turbine on the left and a single stage pump on the right side

(List of reference numbers: see general description of Figure 3)

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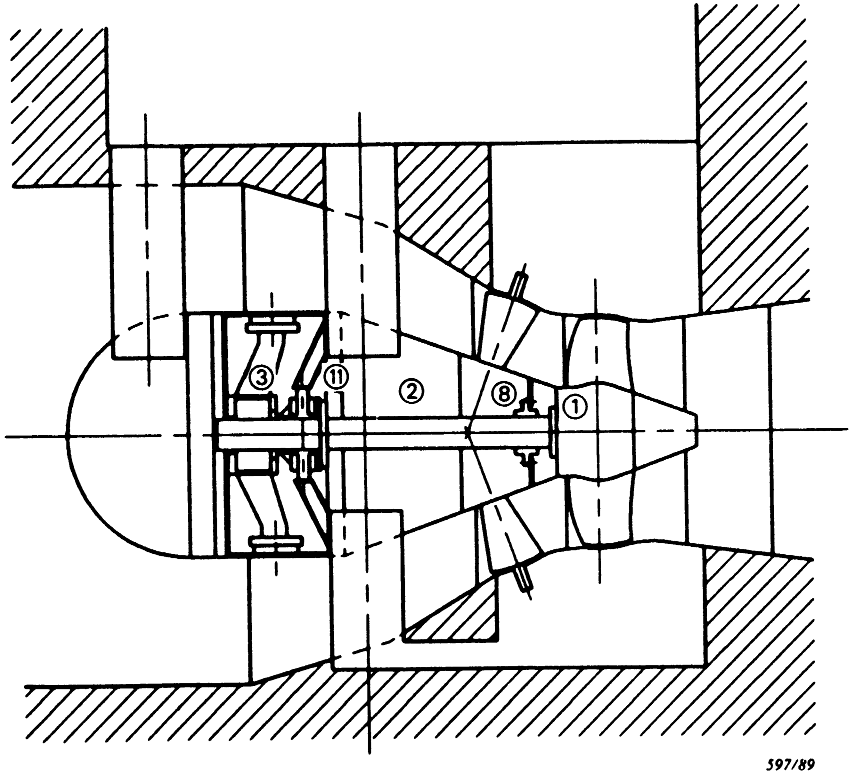

Figure 3h — Example of a bulb machine with a cantilever arrangement of the runner and generator

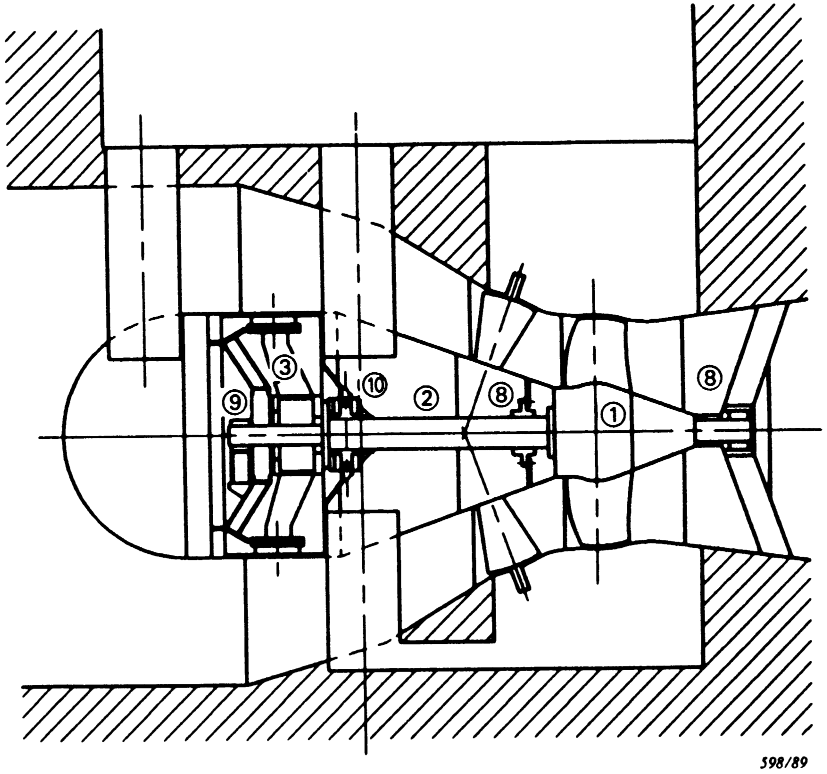

Figure 3i — Example of a bulb machine with an additional radial bearing located on the outlet stayring

(List of reference numbers: see general description of Figure 3)

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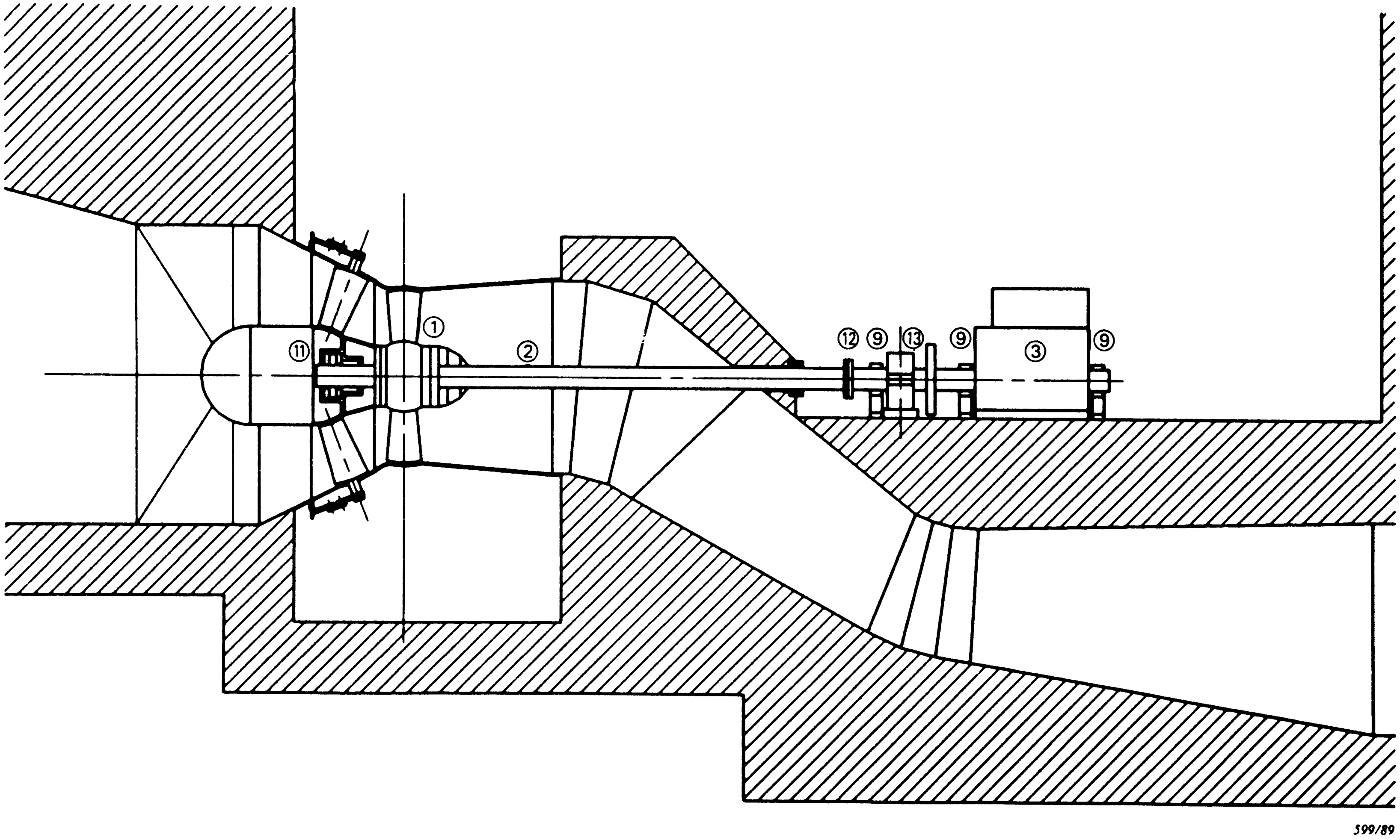

Figure 3k — Example of an S-type machine

(List of reference numbers: see general description of Figure 3)

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3 Guarantees

Guarantees, of whatever nature, do not form part of this guide. The data available at present are not sufficient to determine guarantees actually based on the maximum extent of vibrations and pulsations of hydraulic machines.

In the future it will be possible to determine these quality ranges by statistical evaluation of the results of tests carried out according to this guide.

Nevertheless, if guarantees are given in special cases, they shall refer to this guide as far as measurement procedure is concerned7).

Section 2. Execution of tests

4 Test conditions to be fulfilled

4.1 Operating conditions under which measurements are performed

Operating conditions under which measurements are performed depend on the local conditions, the machine, the intended objectives and are fixed by mutual agreement.

4.1.1 The operating conditions listed below are only an example of conditions of interest under which vibration and pulsation tests may be performed:

a) Machine at no-load and speed increasing step-by-step up to specified speed or, if needed, maximum momentary overspeed.

b) Machine in steady state regime under increasing load and/or under minimum/medium specific hydraulic energy and maximum specific hydraulic energy if necessary.

c) Transients (start-ups, shut-downs, load changes, load rejections, etc.).

d) Machine operating at specified speed, not connected to the system, excitation field switched on and off, to determine if vibration is due to mechanical or electrical unbalance; also and if the generator vibration is influencing the turbine operation8).

Appropriate tests will be performed, if possible, for all the operating modes of importance in which the machine will be required to work.

If several machines are installed in the same powerhouse or system, the machines should be tested (synchronized) separately and together (two or more turbines) to indicate the possibility of interference (hydraulic or electric).

4.1.2 Vibrations and pulsations of the hydraulic machines shall be measured when specific hydraulic energy, discharge and NPSE (net positive suction specific energy) are within the specified limits. Different combinations of these parameters influence the vibrations and pulsations in the machine.

4.1.3 If air admission/injection to the machine water passages is provided for a machine, all the conditions involving air admission/injection shall be included in the operating conditions to be investigated. In this case the admitted/injected air quantity should be measured if possible.

4.1.4 Particularly severe tests (such as steady-state runaway speed, load change from pumping to maximum momentary overspeed with blocked wicket-gates) should not be carried out for the sole purpose of gathering information on vibrations or pulsations; if they are performed at all, then special agreements covering the risks should be taken between owner, manufacturer and test organizers prior to test performance.

4.2 Checks on the machine before the beginning of tests

Every vibration test is referred to one or more operating points of the machine, identified by certain scales and readings (gate openings, blade angles etc.). It should be kept in mind that sometimes the indications given by these scales and readings may not be accurate. Therefore, if at all possible, an inspection (with dewatering of the water passages) should be made prior to the tests, or reference should be made (if available) to a recent inspection (e.g. not older than six months). This inspection should also serve the purpose of checking the exact positions and the good condition of the transducers and pressure taps.

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7) In the meantime, reference could be made, for steady-state operation, to ISO 3945 (clause **8**, table), with due caution as regards the applicability of the said standard to the specific case under consideration.

8) Examples a), b), c) and d) are intended for turbine operation: similar conditions may be defined for pump operation.

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In the absence of these possibilities, agreements as to the meaning and inaccuracies of scales and readings should be reached among the interested parties.

5 Test procedure

5.1 Parameters determining the operating point

5.1.1 *Measurements under steady-state condition*

These measurements should be performed with all the operating parameters — such as: guide-vane or needle opening for a regulated turbine or pump-turbine, valve position for a non-regulated pump or pump-turbine, power, rotational speed and specific hydraulic energy — kept constant during the test. However, in certain small reservoir installations the specific hydraulic energy (head) cannot be kept constant. In these cases a low variation in specific hydraulic energy can be allowed, provided it does not exceed ± 3 % of the specified specific hydraulic energy.

5.1.1.1 The power of the machine shall be measured with panel measuring instruments. Their accuracy should have been previously checked. If higher accuracy is desired, ad hoc instrumentation may be used in accordance with IEC codes.

5.1.1.2 The accuracy of the speed measuring device (calibrated tachometer or impulse counter) should allow the determination of actual speeds under steady-state conditions with an uncertainty of not more than ± 1 % of specified speed (if possible).

A rotational impulse (revolution mark) must be available to determine the phase of vibratory phenomena with respect to a definite radial plane of the rotating part.

5.1.1.3 The specific hydraulic energy can be evaluated by the measurement of the headwater and tailwater levels. If the measurement of these levels does not supply the specific hydraulic energy value with sufficient accuracy, additional pressure taps have to be placed at the machine high and low pressure reference sections from which the specific hydraulic energy as well as the test NPSE can be obtained in accordance with IEC codes.

5.1.1.4 The guide vane (or needle) opening shall be determined from the readings of the distributor (or nozzle) opening scale and/or from the servomotor stroke, with an accuracy of ± 1 % of full opening.

5.1.1.5 In the case of a runner with movable blades, the blade angle should preferably be measured directly. If this cannot be done, the angle should be derived from a component directly coupled to the blades, such as a blade servomotor or a connecting rod. The result should be accurate to ± 1 % of full servomotor stroke or better.

5.1.1.6 For those special cases in which flow regulation is achieved by a main inlet (or outlet) valve (e.g. for non-regulated multistage reversible machines at no-load), the valve opening should be determined with an accuracy of ± 0,5 % of full servomotor stroke (if possible).

5.1.1.7 In addition to the parameters already mentioned, all others which may be of importance to define the operating point have to be measured (e.g. bearing temperature, water temperature).

5.1.2 *Measurements during transient operation*

In normal cases for transient processes (e.g. start-up, shut-down, load change, load rejection in turbine operation, power failure in pump operation, etc.) the relevant parameters should be recorded for a thorough analysis. That means that this not only includes the desired vibration or pulsation parameters but also all parameters (e.g. rotational speed, specific hydraulic energy, guide vane or needle opening, valve opening in certain cases, etc.) necessary to describe the transient operation.

In particular the following must be taken into account:

5.1.2.1 The power of the machine shall be measured by suitable power transducers capable of supplying a signal proportional to the power.

5.1.2.2 The rotational speed shall be measured by means of suitable transducers (such as tachometer dynamos) capable of supplying a signal proportional to the instantaneous speed useful for the recording. The measurement should be performed with a measurement uncertainty not higher than ± 1 % of the specified speed (if possible).

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5.1.2.3 The specific hydraulic energy and the NPSE shall be determined by the measurement of the high-pressure and low-pressure side instantaneous pressure, using suitable pressure transducers connected to the reference pressure taps[9].

5.1.2.4 The guide vane (needle) opening shall be measured by suitable transducers connected to the moving parts of the servomotor or to a guide vane stem.

5.1.2.5 In case of a runner with movable blades, the blade angle shall be measured by special transducers connected to the feedback rod, or, if this is not possible, to the measuring device of the positioner.

5.1.2.6 If necessary, the opening of valves and gates can also be measured by suitable transducers.

5.2 Vibration and pulsation quantities to be measured and locations of measuring points

The quantities to be measured during steady state and transient operation shall be determined case by case depending on the objectives and by mutual agreement between the parties (see also the final part of the Introduction).

As far as measurements of structural vibrations (as distinct e.g. from pressure or power pulsations) are concerned, different kinds of measuring instruments are recommended according to the frequency range to be covered. This range can occur in a wide interval, from a few tenths of a hertz (“low” frequencies) to a few hundred hertz (“high” frequencies), see **6.1.1**.

If “low” frequencies are to be investigated, the mechanical parameter to be measured in order to assess the vibrational state of the machine is usually the displacement (u or d). In the “medium” frequency range, velocity (v) is often measured, while in the “high” frequency domain the acceleration (w) is preferentially measured.

Sometimes it may be advisable to simultaneously measure two of these quantities in order to get more information or to cover different frequency ranges in the same test.

However, particular care must be taken regarding the measurements of the vibrations in transient conditions; in fact in this case the transient response of the transducer must be taken into account too. In particular, the natural frequency and damping factor of the transducer will have to be chosen in relation to the type and duration of the transient expected for the variable to which the transducer is sensitive.

It must be noted that in the case of particularly unfavourable measurement conditions the value of the vibrations can be overestimated or underestimated[10].

5.2.1 The most significant points where vibration is concerned are generally:

a) housing of each guide bearing and support frame of thrust bearing;

b) head cover of the hydraulic machine;

c) generator bearing bracket;

d) non-concreted part of the discharge ring or top of draft tube cone (for Kaplan and bulb units);

e) bulb shell and ribs;

f) guide vanes (for regulated machines);

g) stay vanes in special cases, etc.

In each particular case this list could be extended or shortened, according to the actual conditions.

According to the case, vibration transducers should be positioned as follows:

— on radial lines 90° apart for each guide bearing housing;

— in an axial direction as close as possible to the machine axis of rotation for the thrust bearing support frame;

— on a radial line located as far as possible from the limits of the part of the discharge ring that is not concreted;

— radially and tangentially on ribs at two cross sections within the bulb area, one of them being located near the hydraulic machine guide bearing and the other near the generator;

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[9] In order to obtain the specific hydraulic energy, the kinetic term should also be known. Since a direct measurement is usually not possible, an evaluation of the term can be made if approximate instantaneous discharge values are known. The error thus introduced is not usually important, since the kinetic term is generally small compared with the specific hydraulic energy.

[10] For special cases or provisions, refer to ISO Standards 5348, 8042 and 5347.

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- on any accessible part rigidly fixed to the guide vane and according to the following directions:
  - parallel to the rotation axis of the guide vane;
  - normal to the rotation axis and to the plane of minimum rigidity of the guide vane;
  - normal to the rotation axis and to the previous direction.

5.2.2 *Radial vibrations on the shaft* should be measured near the guide bearings. For these measurements, proximity transducers[11] should be used positioned 90° apart on two radial lines at each measuring section. To measure relative vibrations between shaft and guide bearings, transducers will be fixed on the bearing housing, as near as possible to the shaft. If the absolute vibrations of the shaft are of interest, a stationary base should be provided for the transducers, if possible[12].

Normally it is sufficient to measure the shaft vibrations near the bearing housings. Only under special conditions may it be necessary to measure the flexural oscillations of the rotating shaft at different locations between the bearing housings with reference to a fixed point ("absolute" motion). In this case, in order to have an idea where to put the transducers along the shaft axis, preliminary computations should be carried out, leading to the determination of the theoretical flexural modal shapes of the shaft (these computations will also yield the corresponding theoretical frequencies).

Transducers should then be placed near the locations of maximum amplitude of significant flexural modal shapes. Two transducers along shaft radii at 90° from each other should be used for each location.

5.2.3 *Pressure pulsations* should be measured in significant locations, such as for instance:

a) on the high pressure side of the machine and if necessary in the penstock;

b) in the draft tube and if necessary also in the tailrace;

c) on the wet surface of the head cover, in the interspace between guide vanes and runner/impeller, etc.

Pressure pulsation transducers should be installed:

a) on the high pressure side of the machine;

b) in the draft tube at a distance of 0.5 D_5 to 1.0 D_5 from the point of intersection of the runner/impeller blade centerline and the discharge ring for Kaplan, propeller and diagonal flow machines, and at a distance of 0.2 $D_5 - 0.8\ D_5$ from the bottom face of the band of a Francis runner/impeller, D_5 being the suction diameter.

For curved draft tubes preferred locations are at the inner and outer contour of the elbow.

5.2.4 *Stress pulsations* are obtained by calculations from the measured strains, see Appendix A. The measurements usually are carried out with electrical resistance gauges placed at significant locations like holes, grooves, fillets or particular points of the modal shape with concentrated stresses and a higher risk of fracture (e.g. Pelton bucket roots).

5.2.5 *Shaft torque pulsations* can be obtained by measurement of the torsional strains at suitable locations on the shaft between the runner and the electrical machine (see Figure 5 and Appendix B). Locations with a reduced torsional stiffness are preferred due to a better resolution of the signal. Signal transmission from the rotating to the non-rotating part can be made by means of slip-rings or a contactless transmitter device.

5.2.6 *Rotational speed pulsation* can be measured with optical, magnetic or other devices. It can be measured at any accessible location on the shaft, but it should be noted that measurements taken at different locations could yield different results, in the case of long shafts, due to their torsional oscillations.

5.2.7 If the *power pulsations* in question are those of the electrical machine, the electrical quantities at the input of a motor or output of a generator have to be measured. These include the network excitation or reaction, if any.

The pulsations of the mechanical power in the shaft can differ from those of the electrical power due to rotational inertia effects. Mechanical power pulsations can be obtained by calculation if the shaft torque and rotational speed have been measured at the same location of the shaft.

5.2.8 *Guide vane torque pulsations* can be measured at the guide vane stem or at the guide vane link by means of a strain measurement (see Figure 6 and Figure 7 and Appendix B). The bearing friction influences the results to an unknown extent.

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[11] The proximity transducers give the dynamic relative displacement of two vibrating points with respect to one another [see **2.3.1.4**: d (*t*)].

[12] If not possible, see the recommendations of ISO 7919.

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5.2.9 *Radial thrust pulsations at guide bearing* can be measured by means of strain measurements. In tilting-pad bearings the forces have to be measured in the pivot of each shoe to find the resulting bearing force. With all other bearing types difficulties arise if no provision for the measurement is made at the design stage of the bearing. In such cases strain measurements in the bearing supports could be acceptable. The installation of two transducers located at 90 degrees from each other is to be provided for whenever possible.

5.2.10 *Axial thrust pulsations at the thrust bearing* can be evaluated as:

a) reaction pulsations on the supporting structures, by means of strain or deflection measurements on members whose stiffness can be determined or calibrated (e.g. by jacking);

b) thrust bearing load pulsations, by means of strain measurements on every bearing element;

c) axial load pulsations on the shaft, by means of longitudinal strain measurements, through strain-gauges duly compensated (see Appendix B).

5.3 Personnel

5.3.1 Unless otherwise provided for in the contract, the contracting parties shall jointly select the test personnel and the test methods and procedures.

5.3.2 A Chief of Test shall be appointed by agreement between the parties concerned. He shall manage and supervise the test and report on test progress and results. He shall be responsible for the computation of results and the preparation of the final report. On any question pertaining to the execution of tests, his decision shall be final.

5.3.3 The purchaser and the supplier shall be entitled to have members of their staff present, at least as observers.

5.4 Agreement of test procedure

5.4.1 As a rule, vibration and pulsation tests are carried out at the request of the purchaser, or of the supplier after mutual agreement.

5.4.2 The procedure to be followed in the test shall be established by the Chief of Test. All arrangements and the plan for the test are to be submitted to the purchaser and supplier in ample time for consideration and agreement.

5.5 Test programme

The programme of tests is drafted by the Chief of Test taking into account the requirements of the following sub-clauses; it is to be submitted to the purchaser and supplier for agreement. The programme shall include particulars concerning the following items:

5.5.1 *Purpose of the test*

This shall comply with clause **1**.

5.5.2 List of quantities to be measured and location of transducers.

5.5.3 *Scope of preparatory work*

Preparatory operations shall be listed and their duration stated for the cases of machine operation and shut-down.

5.5.4 *Detailed list of scheduled tests*

This shall include a statement on test conditions, duration of test runs, total duration of the test; also the quantities to be measured under each of the operating conditions shall be indicated. Operating conditions and checks specified in **4.1** and **4.2** shall be included in the test programme.

5.5.5 *Measuring equipment*

Instruments and methods to be used for measurement and recording of all the quantities included in the programme shall be stated. Furthermore, a detailed description of the calibration procedures utilized shall be supplied. The tasks of persons responsible for the measurements shall also be stated (the power station personnel may perform certain measurements).

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5.6 Preparations for tests

5.6.1 All necessary records and reports on the latest inspection of the machine (after erection, commissioning or the latest repair) and on its operation shall be examined and the machine itself shall be inspected. The purpose of this is to verify, as far as possible:

a) that the machinery is complete according to specifications;

b) that the scales of guide vane or nozzle opening and runner blade angle correspond with actual measurements taken;

c) that water passages are not obstructed or restricted by any foreign material;

d) that no undue wear of important parts has taken place;

e) that clearances in the bearings conform to specifications;

f) that alignment of the shaft is within the acceptable limits;

g) that no test condition listed in the programme lies outside the permissible range of operation of the machine.

5.6.2 A communication system shall be provided between the stations where measurements are carried out.

5.6.3 Transducers shall be installed at points specified in the test programme.

5.6.4 After completion of installation of amplifiers, recorders and their connecting lines, all instruments shall be checked and made ready for use.

5.6.5 It is recommended that a transducer layout diagram should be drawn and reference numbers or designations should be assigned to all transducers. The following information is recommended to be given in tabular form:

- — transducer location;
- — reference number or designation;
- — transducer type and serial number;
- — identification of each cable or wire;
- — type and serial number of amplifier, recorder and analyser;
- — identification of each measuring channel.

5.6.6 Calibration of instruments shall be carried out after mounting or at least on site as far as possible. All instruments which cannot be calibrated on site shall be provided with up-to-date calibration documents. Prior to the official tests, scales of all recorded quantities and the speed and duration of recording shall be determined. Upon completion of the tests, calibration shall be repeated as far as possible. The repetition of calibration may be omitted by special agreement.

5.6.7 Upon completion of the preparations the Chief of Test certifies that the preparations have been made in accordance with the test programme or makes an agreement on deviations from the programme.

An agreement of all parties concerned is essential on measured quantities, instruments and operating conditions under which the measurements will be made.

5.7 Observations

5.7.1 The test is carried out under the operating conditions specified in the programme. All characteristic quantities are recorded during each test run. Sample forms of the observation sheets are given in Appendix C (see Figure C.1 and Figure C.2). The Chief of Test can express his personal opinion (estimate) on the vibrational state of the unit or its structural part directly on the observation sheet for each test run.

5.7.2 Sufficient information shall be recorded during the tests, so that all conversion factors can be computed and all individual records can be coordinated with respect to the test run.

5.7.3 All readings or recordings for any given test run shall be taken at the same time, this being ensured by an optical and/or acoustic signal sent simultaneously to all observers. An electrical synchronizing signal shall be recorded by all recording instrumentation, whenever possible.

5.7.4 If readings or recordings are to be taken during steady state operation, the starting signal shall be given a sufficient time after the position of a runner vane or nozzle and/or guide blade has changed[13].

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[13] The elapsed time should in each case ensure that a new steady state condition has been attained.

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5.7.5 Pulsations should be measured simultaneously with vibrations during the tests.

5.7.6 Preliminary data processing is done during the tests or immediately after the tests. The test results and the data concerning test conditions are recorded on the observation sheets; blank samples of such sheets are shown in Appendix C.

5.8 Repetition of tests

After completion of the tests the records shall be examined by all parties concerned and representative results shall be provisionally computed on site before dispersal of the testing staff. If there is any dissatisfaction with a test for clearly explained reasons, the dissatisfied party shall have the right to ask for the tests to be partly repeated.

Section 3. Methods of measurement, data acquisition and processing

This section deals with the determination of values characterizing vibrations of various parts and assemblies of hydraulic machines (see **5.2.1** and **5.2.2**), pressure pulsations in water passages (see **5.2.3**) and other values required to obtain vibration and pulsation parameters described in Sections 1 and 2 of this guide. Recommendations are given on the arrangement of measuring systems and the selection of their separate elements.

Among the different pulsations to be measured, strain pulsations may be particularly important due to the fact that usually it is not possible to indicate precise allowable limits for kinematic vibration parameters, i.e. displacements, velocities or accelerations. Hence, in doubtful cases the ultimate judgement on the acceptability of vibration levels may hinge on the strain (stress) pulsation level.

Therefore, some recommendations on procedures for using strain-gauges are also given in this section, together with recommendations for other vibration or pulsation measurements.

The measurement results should be tabulated, e.g. as shown in Appendix C.

The signals may be recorded and processed as follows (see clauses **8** and **9**):

— graphical recording of a parameter as a function of time (oscillograms)[14];

— recording of r.m.s, and/or peak-to-peak or peak values by means of a digital recording instrument or other indicating device;

— time dependent parameter recorded analogically or digitally on magnetic tape or in digital storage for subsequent reproduction and analysis[14];

— power density spectrum.

Only instruments reliably checked or calibrated with the reference ones for the whole range of modes of operation, amplitudes and frequencies should be used for the measurements (see clause **7**).

6 Considerations relating to the methods of measurement

6.1 Vibrations

6.1.1 For selecting the measuring means, it is necessary to determine the upper and lower frequency limits of the expected vibrations and pulsations. They are influenced by the frequency spectrum of the exciting forces as well as by the natural frequencies of blades, buckets, vanes, etc.

In the absence of other indications the following relations can be used, if possible:

a) Lower frequency:

$f_L = 0.1\, f_{sp}$[15]

where f_{sp} = rotational frequency at specified speed.

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[14] Together with a rotation indicator to record phase with respect to the angular position of the shaft, whenever necessary and possible.

[15] In the case of a Francis turbine, e.g., the lower measurement frequency must be lower than the vortex rope frequency, normally between $^1/_4$ and $^1/_2$ of f_{sp}, at partial load.

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b) Upper frequency[16]:

— for Pelton turbines:

$$f_U = z_2 \cdot \frac{2\pi}{\varphi_n} \cdot f_{sp}$$

where φ_n = minimum angle between axis of nozzles (in radians), if the nozzles are not symmetrically distributed and $\varphi_n = 2\pi$, if $z_0 = 1$,

— For other types of machine:

$$f_U = \max\left[z_0 \cdot z_2 \cdot f_{sp};\ S \cdot \frac{v_w}{\delta}\right]$$

where S = a suitable Strouhal number[17]

The instrumentation has to be selected according to the expected frequency range; if necessary, a combination of different measuring channels can be used to cover the whole range.

It must be considered that in the case of measurements during transient conditions, the natural period of the transducer as installed should be as short as possible with respect to the input pulse duration.

For instance a reasonable ratio between pulse duration and natural period would be of the order of 5 to 1 if the transducer is not damped; see ISO Standards 8042 and 5347.

6.1.2 The measuring channel may be constructed, for example, in accordance with the block diagrams of Figure 4.

In particular, Figure 4 *a)* shows an example of a simple arrangement suitable for tests under steady-state conditions and, with an adequate recorder, for simple transient tests, whereas Figure 4 *b)* shows an example of a more complete arrangement of the measuring chain which can be used to advantage during transient tests for which recording on magnetic tape or in digital storage is fundamental.

6.1.3 It is recommended to use specific transducers for each vibration parameter (displacement, velocity and acceleration).

When a certain parameter is not directly measurable due to the lack of the specific transducer, integration or differentiation of the output of another transducer could in theory sometimes supply the answer. Even if integrating or differentiating devices are available, however, their application requires particular caution as they may introduce large errors into the chain output.

Since the minimum f_{Lr} frequency measurable by vibration transducers which are commonly on the market can be higher than the minimum f_L frequency to be measured, the frequency limits in the whole measuring channel should be known, if only from factory calibration.

The transducers to be used should have the frequency response not deviating from linear more than ± 1.5 dB over the frequency range chosen within the interval $f_L - f_U$[18].

Transducer sensitivity should be adequate to obtain a level of minimum signal to be measured exceeding the level of the lower limit of the dynamic range of the measuring channel by 10 dB (about 3 times) as a minimum.

On the other hand, the sensitivity should not be so great that the maximum signal to be measured may overload the measuring channel.

The lower limit of dynamic range is determined during vibration measurement by the measuring system noise. The noise of electronic circuits constitutes the main part of the noise.

Earth loops may be one of the causes of excessive noise.

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[16] In some cases, disturbances with even higher frequencies than the limit indicated by the above formula can be found, e.g. at frequencies of the order of 1 000 Hz, 2 000 Hz or even more, (this can be related to the natural frequencies of bucket vibration, etc.). Whenever this is of relevance to the test results, f_U should be fixed accordingly.

[17] As a first approximation $S = 0.15$ to 0.25 can be used (see Figure 1 and Figure 2).

[18] When this is not possible, an upper deviation limit of ± 3 dB from linear could sometimes be tolerated. Otherwise, adequate frequency-dependent compensation should be made during measurement or data processing based on the actual response curve of the measuring channel.

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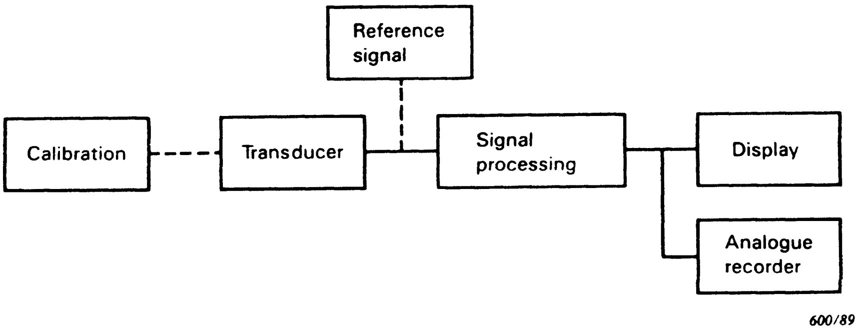
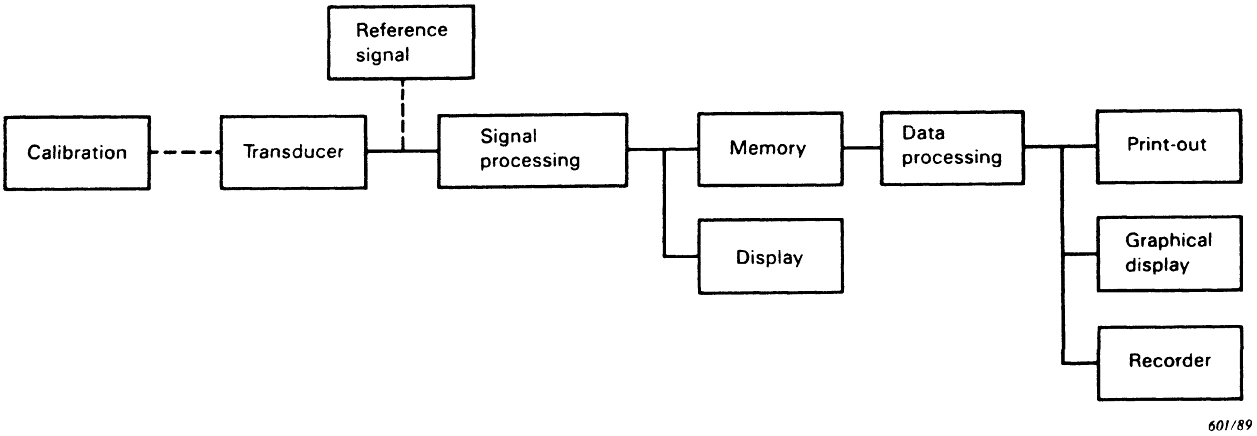


a) Simple arrangement



b) Complete arrangement

——— Permanent connections

– – – Temporary connections (for calibration only)

Figure 4 — Basic combination of units for a measuring and analysis system for vibration parameters

To reduce noise in the measuring system, it is recommended to electrically insulate the transducer from the investigated object.

The alteration produced by the mass of a transducer employed for field vibration tests of hydraulic machines on the frequency or the vibrating modal shape of the structures to which the transducer is attached is usually negligible.

If special supports have to be used for fastening the transducers to the vibrating part, special care should be taken in order to ensure that this connection has adequate stiffness.

The natural frequency of the support with the transducer mounted shall be sufficiently higher than f_U.

The methods used for specifying the characteristics of transducers shall comply with IEC Publication 184.

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6.1.4 The complete measuring chain, including transducers, amplifiers, data processing and data storage equipment has to be carefully selected so that the required frequency range for each individual channel is provided.

It has to be checked whether the frequency range is better covered by the use of displacement[19)], velocity or acceleration transducers.

In some cases two different types of transducers should be used to cover different parts of the frequency range.

The use of integrating stages in the preamplifiers should be avoided if possible, because it may lead to non-predictable measurement errors or inaccuracies (see also **6.1.3**).

It has to be checked very carefully that the combination of transducer, preamplifier and cable will not affect the measuring accuracy and will not cause an increase of the electronic noise level.

6.2 Radial vibrations of the shaft relative to the bearings

6.2.1 For the measurement of shaft vibrations relative to the bearings, contactless relative displacement transducers are recommended.

The transducers are mostly mounted on the housings or on the supporting structures of the bearing.

6.2.2 Only in the case of measurement of the flexural vibration modes of the rotating shaft, may it be necessary to mount the transducers on non-vibrating supports far from the bearings (see **5.2.2**).

6.3 Pressure pulsations

6.3.1 The measuring instruments, especially amplifiers, should comply with IEC Publication 222.

6.3.2 The measuring channel may be constructed in accordance with the block diagrams of Figure 4 (see **6.1.2**). The transducers should possibly be fixed flush with the wet wall, otherwise special care shall be taken to eliminate the risk of resonance and damping effects in the connecting pipe (see Appendix D). The above fixing should also minimize the sensitivity to mechanical shocks and avoid secondary oscillations in the connecting pipe.

6.3.3 The required frequency range of the measuring chain shall at least meet the conditions indicated in **6.1.1**. The d.c. (zero frequency) response, if possible, should be included.

6.3.4 The measuring chain resolving power should be 0.5 % (or better) of the pressure difference corresponding to the specific hydraulic energy value. It is desired that measuring chain dynamic range should be not less than 40 dB (a factor of 100).

6.3.5 *Transducers*

The transducer should withstand, without changing its sensitivity and natural frequency, the maximum possible pressure (including water-hammer) in any measuring point. Deviation of the transducer amplitude characteristic from linearity should not exceed ± 1 % of the nominal value (full scale) of the transducer.

6.4 Stresses

6.4.1 It is recommended that the stresses should be measured by a strain-gauge method with the use of a bridge-type circuit.

6.4.2 Amplifiers should be selected in accordance with the requirements of the chosen strain-gauges in the frequency range of interest within the interval from 0 Hz to f_U (determined as in **6.1.1**).

6.4.3 It is recommended that for temperatures from 0 °C to 60 °C wire, foil or other type gauges as sensing elements should be used, provided their properties are as follows:

- — strain measuring range: $-2\,500$ to $+2\,500 \cdot 10^{-6}$ m/m;
- — standard deviation of the strain sensitivity coefficient for a batch of transducers not more than 3 % of average of declared coefficient;

[19)] Displacement transducers can be of two types:

- — with seismic mass (absolute displacement: frequency range with a lower limit dependent on the seismic mass and its suspension system);
- — relative displacement transducers, e.g. proximity transducers (between the vibrating point and a support, considered as fixed. Lower frequency limit = 0);

see also **5.2.2**.

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— transverse deformation effect: not more than 5 % of longitudinal deformation effect.

Temperature compensation should be provided if necessary.

6.4.4 Strain gauge sensitivity coefficient (K factor) should be known. It should be stated in the certificate provided by the manufacturer.

6.4.5 Fixing of strain gauges shall be exactly in accordance with the instructions of the manufacturer. Careful insulation against humidity shall be provided.

6.4.6 Three directional "rosettes" should be used to determine the magnitude and direction of the principal stresses, see Appendix A. In many cases, when the direction of the principal stresses is well known, less than three measuring directions can be used.

6.5 Shaft torque pulsations

6.5.1 *Transducers*

Shaft torque pulsation can be determined e.g. with strain gauges, if these are arranged so that they only measure torsion (and not simultaneously also bending or axial strain) of the shaft (see Figure 5). The resolving power of such a measuring system is frequently not particularly high due to the stiffness of the shaft. An estimation of the attainable resolving power prior to the measurement is recommended.

6.5.2 *Transmission*

For the transmission of the torque transducer output signal from the rotating shaft to the stationary equipment it is possible to use:

— slip rings;

— contactless capacitive or inductive transmitters;

— rotating transmitters and stationary receivers of electromagnetic waves.

It is to be noted that the noise occurring in these transmitters frequently limits the resolving power of the entire measuring chain.

6.6 Rotational speed pulsations

Rotational speed pulsations can be measured in the analogue or digital mode[20].

In the analogue measurement one obtains the measuring signal usually from a frequency generator or a tachometer coupled with the machine in some way. The speed proportional frequency picked up is converted into an analogue signal whose amplitude fluctuations indicate the speed fluctuations.

With a digital measurement of speed fluctuations a frequency generator is to be used. In this case the time interval (period) between two pulses is measured with a sufficiently fast time measuring instrument. The measured values have to be recorded digitally (see **8.3**) and evaluated after the measurement by suitable methods.

6.7 Power pulsations

During steady state operations, power pulsations can sometimes be observed. These pulsations can be determined by measuring the electrical output of the generator or the electrical input of the motor (see also **5.2.7**).

By the same measuring arrangement, power changes during start-up, shut-down and load-change transients can normally be observed. However, for special transients, such as load rejection, this technique is no longer applicable and the only technique applicable is that of shaft torque and rotation speed measurement (see **6.5** and **6.6**). If the pulsations to be measured are those of the mechanical power, one should also take into account the fact that they are not coincident with the pulsations of electric power, the difference being made up by pulsations of the power necessary to accelerate or decelerate the rotating masses (the pulsations of the electrical and mechanical losses can be taken as negligible for steady-state tests).

6.8 Guide vane torque pulsations

These measurements are made on turbines and pump-turbines or pumps with regulation. The transducers can normally be only outside the guide vane bearings and for this reason the measurement is influenced to an unknown extent by friction.

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[20] Special care has to be taken because some speed measuring equipment has an inherent time-delay.

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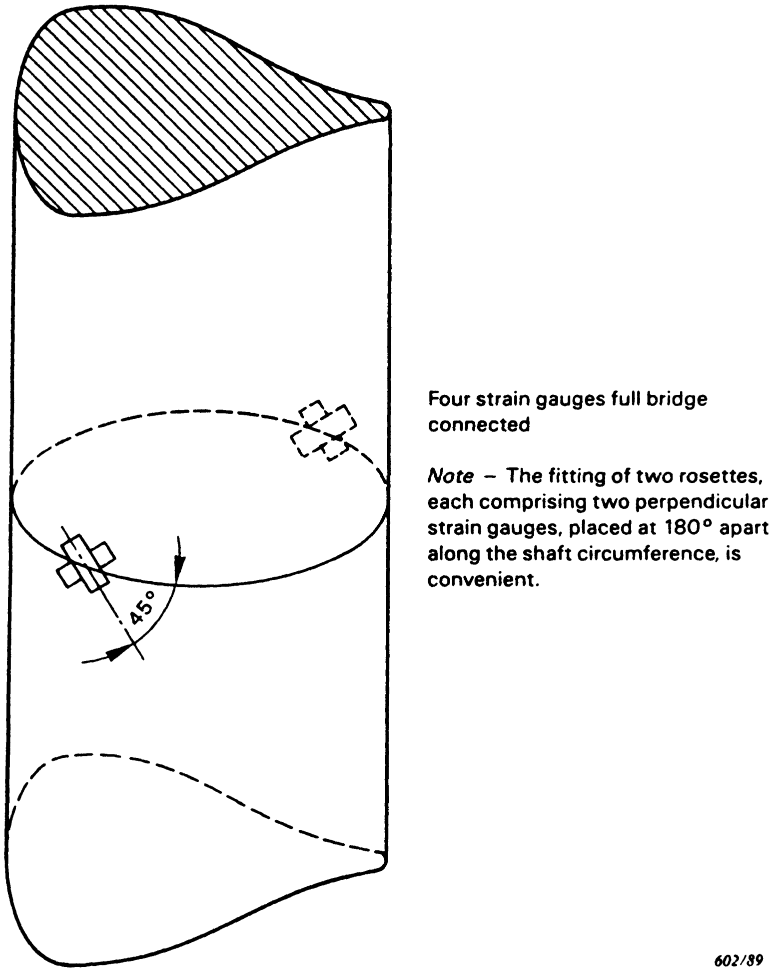

Four strain gauges full bridge connected

Note – The fitting of two rosettes, each comprising two perpendicular strain gauges, placed at 180° apart along the shaft circumference, is convenient.

Figure 5 — Strain gauge arrangement for torque measurement

The torque can be measured in two ways:

- — with strain gauges fitted on the stem in such a way that influences, if any, due to bending of the stem, are eliminated (see Figure 6);
- — with strain gauges fitted on the link at a suitable location (see Figure 7) in such a way that influences, if any, due to bending of the link member, are eliminated. From the force on the member measured in this way, the torque on the guide vane may be calculated taking into account the geometry of the system. See also Appendix B.

6.9 Radial thrust pulsations measured at the guide bearings

Since in many cases it is impossible to accurately measure the radial thrust on the runner by direct methods, it is preferable to refer to radial thrust measurements at the guide bearings.

The force on a bearing can be measured by providing a sufficient number of segments with suitable transducers (e.g. strain gauges).

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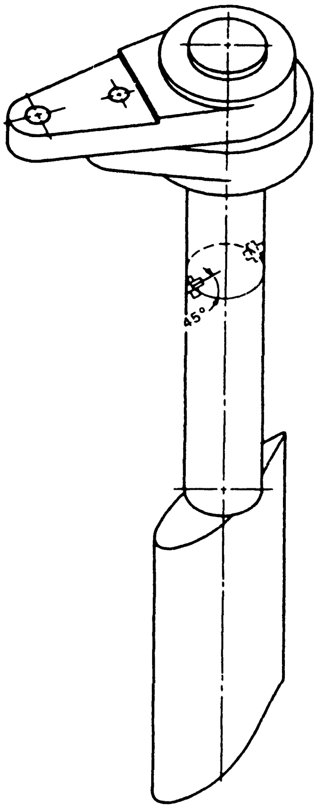

Four strain gauges full bridge connected

Note – The fitting of two rosettes, each comprising two perpendicular strain gauges, placed at 180° apart along the shaft circumference, is convenient.

Figure 6 — Guide vane stem with strain gauges for torque measurement

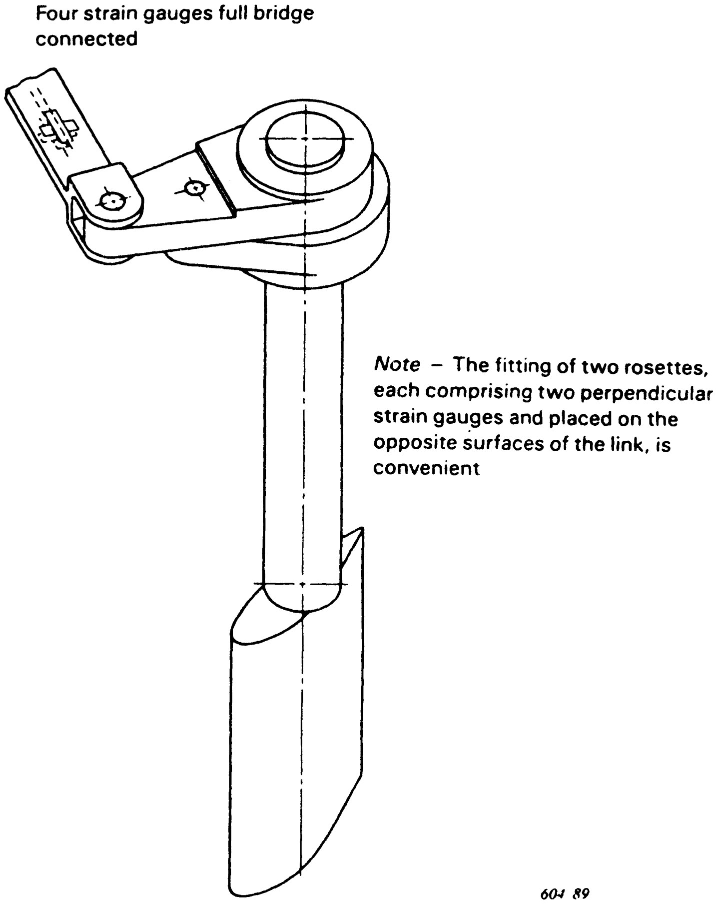

Figure 7 — Torque measurement on one guide vane by means of strain gauges applied on the link

Some manufacturers attempt to get an indication of the radial thrust pulsations on the runner by measuring the clearance variations on the runner band by means of two contactless displacement transducers located at 90° from each other, or from measurements of the shaft bending stresses between a cantilever-mounted runner and the nearer bearing.

However, to get from these measurements an evaluation of the radial thrust pulsations on the runner, an interpretation of the shaft bending pattern would be necessary.

6.10 Axial thrust pulsations measured at the thrust bearing

Accurate measurement of the axial thrust pulsations can only be achieved by preparing the machine in the factory, providing it with special arrangements (e.g. fitting an adequate number of the segments with strain gauges, or measuring the oil pressure in a closed chamber under the bearing, etc.). Only approximate indications of the axial thrust pulsations can be achieved by the following methods:

- — put strain gauges on the fixed structure supporting the thrust bearings;
- — measure the deflection of a fixed part of the thrust bearing (e.g. with a proximity transducer connected to the wall);
- — measure the axial displacement of the shaft (e.g. with a proximity transducer sensitive to the position of a ring protruding from the shaft), etc.

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6.11 Measured quantities defining the machine operating point

The values are ascertained and compiled in the usual way by reading off from the associated instruments and by incorporating them into tables (see Appendix C).

In the event of further processing of the measured values in an EDP[21] system, they are to be entered separately.

Recording these values in a continuous way during the tests together with the vibration and pulsation values is required only in the case of data that may be subjected to wide variations with time.

Among them are:

- the opening of spherical valve, butterfly valve, or gate;
- the guide vane or needle(s) opening, runner blade angle;
- the machine rotational speed (in load rejection tests);
- the machine power;
- high and low pressure side instantaneous pressures.

7 Calibration

7.1 General

The calibration of the measuring system has to be carried out before and, as a check, after performance of the tests. For long duration measurements it is recommended to also carry out the check calibration at intervals throughout the tests. The calibration should be performed for all measuring ranges (magnitude, frequency and phase, if necessary) occurring during the tests. The methodology, the extent and the results of the calibration procedures have to be stated in the test programme and included in the final report.

The calibration signals are to be recorded and/or stored using the same recorder and/or storage equipment as for the measurements.

One of the following two methods is normally used:

- direct calibration of the complete measuring channel including transducers, amplifiers, filter elements, connecting cables and recording instruments. In this method the calibration signal is produced by a direct excitation of the transducer in a well defined manner;
- calibration by electrical reference signals excludes normally only the transducer's signal, simulating the transducer by an accurately known electrical signal.

Static or dynamic calibration procedures may be used depending on possibilities, necessities and method of calibration.

The long-term stability of the most modern measuring systems and especially of the transducers makes it unnecessary to perform direct calibration in most cases. Also it should be taken into account that in some cases the necessary expenditure of work and equipment to perform these calibrations in the plant is too high for the limited importance of the planned measurement.

But in principle the technical data, e.g. sensitivity and frequency behaviour, of all measuring systems should be ascertained periodically by direct calibration or at least after manufacture in an official laboratory or in the manufacturer's laboratory. A certificate should be available.

7.2 Direct calibration

7.2.1 *Vibration measurements*

The calibration is performed prior to the test measurements in the required frequency and amplitude range. For transducers with seismic mass a special vibrostand is used for dynamic calibration. Vibration parameters of the vibrostand (acceleration, velocity and displacement) are measured with an optical device or with a reference vibrotransducer. This procedure is intended essentially for steady state vibration measurements. For transient vibration measurements, special precautions have to be taken, which are dealt with in ISO Standards 8042 and 5347. In most cases it is not possible to perform these calibrations on site because the expenditure on equipment is too large and the time needed for the calibration tests is too long. These tests are normally performed in specially equipped laboratories. Sufficiently recent certificates should be available.

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[21] EDP = Electronic Data Processing.

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If relative displacement transducers are used for the measurements a static direct calibration check should be performed by measuring an applied constant displacement with a device of sufficient accuracy and applying the transducer against the actual surface.

7.2.2 *Pressure pulsation measurements*

The calibration pressure is applied to the transducer by a hydraulic press and is compared with a calibrated precision manometer or dead weight manometer, or by the pressure due to a water column of known height and known temperature (static calibration). A calibration of the dynamic behaviour of the transducers cannot usually be performed on site.

7.2.3 *Stress measurements*

A direct calibration is possible only if the strain measurement is used for the measurement of a force. But also in this case it is impossible under normal circumstances to perform these calibrations on site. The part equipped with the strain transducers has to be removed and a known force has to be applied to it. This is normally done in specifically equipped laboratories.

In all other cases a calibration with reference signals has to be performed, carefully considering the technical data of the strain gauges.

7.2.4 *Shaft torque pulsation measurements*

Normally the measurement of torque in large machines can only be performed by an array of strain gauges applied to the shaft of the machine (see Appendix B). Under normal conditions a direct calibration of the measuring arrangement is not possible.

An approximate static calibration with sufficient accuracy may be performed by measuring the generator output (motor input) at nominal speed and calculating the resulting shaft torque considering the mechanical and electrical losses.

7.2.5 *Rotational speed pulsation measurements*

With the normally attainable accuracy in rotational speed measurements, rotational speed pulsations in steady state tests usually cannot be measured in a precise way, since they are often very small in comparison with the specified speed. On the contrary, large variations in rotational speed during transients can be measured with sufficient confidence.

Normally, no direct calibration of the equipment for the measurement of the rotational speed is necessary, a static check with the panel instrumentation being considered sufficient. If necessary, the instruments may be calibrated e.g. with a pulse train generator and/or a frequency meter (in analogue methods).

7.2.6 *Power pulsation measurements*

A calibration of the equipment for measurement of electrical power can seldom be done on site. A check of correct connection can be made by comparison with the switchboard meters. Equipment for the measurement of electrical power, wattmeters, volt- and amperemeters, normally are calibrated in specialized laboratories.

For the measurement of pulsations a continuous recording is necessary. The recorder should be calibrated using the readout of the laboratory calibrated precision wattmeters at steady state operation, its transfer function having been previously established.

7.2.7 *Guide vane torque pulsation measurements*

A direct static calibration on site cannot be performed under normal circumstances. If a factory prepared guide vane is used for this measurement a static calibration may be possible in factory or in a specialized laboratory, applying a well defined torque to the shaft (or force to the link). (See Appendix B.)

7.2.8 *Measurement of thrust pulsation at guide and thrust bearings*

A direct calibration on site cannot be performed under normal circumstances. Often factory prepared measuring arrangements are used. In these cases a static calibration in factory may be possible by applying well defined forces to the bearing segments used for the measurement. In some cases a calibration is possible by lifting up the rotor using the brakes in the case of a vertical shaft and accurately known rotor weight.

7.2.9 *Guide vane (needle) opening, runner blade angle, valve and gate opening measurements*

Generally, it is possible and also convenient to statically calibrate the position transducers used at site after their installation.

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7.3 Calibration by electrical reference signals

The transducer is not included in this calibration. The technical data for it have to be known from laboratory calibration or as type data for transducers manufactured with small tolerances, e.g. strain gauges.

Usually a static or dynamic reference signal generated internally by the measuring amplifier is used for the calibration. In some cases an externally generated reference signal is used.

7.3.1 *Vibration measurements*

Normally an internal signal generator feeds an electrical signal of defined amplitude and of defined frequency to the amplifier input so that amplifier and recording instrument assemblies can be calibrated.

7.3.2 *Pressure pulsation measurements*

Normally the amplifier and bridge assembly is calibrated by static internally generated signals of positive and negative polarity. The recorder is included in the procedure.

7.3.3 *Stress measurements, strain measurements*

The amplifier, the bridge and the recorder are calibrated by internally generated static signals.

7.3.4 *Shaft torque pulsation measurements*

Since in principle this measurement is a strain measurement, see **7.3.3**.

7.3.5 *Rotational speed pulsation measurements*

Indirect calibration by an electrical reference signal is possible when the output of the transducer is an analogue signal.

7.3.6 *Power pulsation measurements*

Only the recorder can be calibrated if the output of the measuring instrument is known.

7.3.7 *Guide vanes torque pulsation measurements*

See **7.3.4**.

7.3.8 *Measurement of thrust pulsation at guide and thrust bearings*

The amplifier, the bridge and the recorder are calibrated by internally generated static signals. The relation between transducer output and thrust has to be known from calculations or laboratory tests.

8 Recording

Direct recording by strip chart recorder, magnetic tape or digital recording should be used.

In comparison with the manual recording of the read-out of a scale or digital instrument, direct recording by strip chart recorder, magnetic tape recorder or digital recording has the following advantages:

- — by continuous recording the process can be investigated over short time intervals, of the order of the signal variation time;
- — very short transient processes can be observed;
- — various signals can be recorded simultaneously and can be compared later;
- — the direct measuring signal is stored for later evaluation or check;
- — in the case of magnetic tape and digital recording, the measuring signal can be played back as often as necessary for further investigations (e.g. peak or r.m.s. analysis, frequency analysis, etc.).

The accuracy of the recording system should be matched, whenever possible, to the accuracy of the measuring equipment.

8.1 Graphical recorders

8.1.1 *Usable types of recorders*

For the purpose of recording, it is necessary to use a recorder with an upper frequency limit appropriate to the highest frequency of interest contained in the signal.

Examples of the commonly used types of recorders are:

- — galvanometric recorder with optical or ink recording system;
- — electronic recorder with thermal or electrostatic recording system.

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8.1.2 *Selection of writing speed*

The writing speed is selected in accordance with the instructions given in the instrument manuals and with the desired time resolution.

8.1.3 *Selection of paper speed and recording time*

The recording time t_r is determined by the component frequency f_i to be considered and the number of cycles N_r of this frequency which should be contained in the record. Recording time should be calculated from:

$$t_r = N_r \cdot \frac{1}{f_i} \tag{8}$$

If the length of the record corresponding to one cycle is l, then the total length of the record is:

$$L = N_r \cdot l \tag{9}$$

Then the required paper speed is:

$$v_r = \frac{L}{t_r} = l \cdot f_i \tag{10}$$

The number of cycles N_r to be contained in the record depends on the characteristic of the spectrum and shall correspond to the method of analysis used. The length l corresponding to one cycle should be chosen according to the line thickness, so that one oscillation cycle may be clearly made out on the graph.

8.2 Magnetic tape recorders

8.2.1 Use of magnetic tape recorders allows multiple reproduction of the recorded signals and makes it possible to use electronic equipment and computers for analysis.

8.2.2 The frequency range of the tape recorder employed should be wider than the range to be measured. FM (frequency modulated) systems are to be preferred to AM (amplitude modulated) systems as FM systems allow the frequency range to start from zero frequency. In this case, however, particular attention should be paid to the upper boundary frequency of the FM recorder. Also multichannel tape recording with the PCM (pulse code modulation) system is possible. The measured values are in this case recorded in a digital code.

8.2.3 Multichannel tape recorders should be provided with a separate channel for the recording of a time signal or another mark or voice signal so as to be able to identify any point on the magnetic tape in the subsequent analysis.

8.2.4 Multichannel tape recorders should be used for simultaneous recording of several parameters. An electronic oscilloscope or a graphical recorder connected to the output amplifiers of the tape recorder should be used for recording supervision if the instrument is equipped with a simultaneous record-playback feature. Otherwise, at suitable intervals all records have to be played back off-line on a strip chart recorder to check the quality of the recording.

8.2.5 *Selection of tape speed*

The tape speed has to be selected according to the instruction manual, taking into account the highest significant frequency in the signal.

8.3 Digital recording

The special advantages of digital data recording are:

- — no drifting of the zero points on reproduction;
- — perfect reproducibility;
- — digital storage of parameters, such as calibration values, conversion factors, port selection, scanning rate, time, etc.;
- — output in engineering values.

The number of bits for the A/D conversion should be sufficiently high to cover the dynamic analog to digital range of the measurements.

8.3.1 *Series data recording*

This type of recording is only suitable for slow, quasi-stationary operations or for supervision of operation (endless loop).

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For data storage, several storage media can be used, with widely variable recording speeds.

8.3.2 ***Sequential data recording***

Sequential recording is particularly suitable for storage of transient operations in blocks. After each measurement the data collected in the computer are transmitted to the data memory.

The maximum record time T_{rm} is limited by the storage capacity of the RAM (random access memory) of the computer. It may be calculated by the following formula:

$$T_{rm} = \frac{C_s}{n_{ch} \cdot s_{rch} \cdot b_s}$$

where:

C_s = storage capacity of RAM in bytes
b_s = number of bytes per sample
n_{ch} = number of channels
s_{rch} = sampling rate per channel

This limitation has to be taken into account when planning the instrumentation of the measurement, since the minimum necessary record time depends on the measured physical quantities and on the analyses which are planned.

8.3.3 The sampling rate of each channel is to be adapted to the measuring requirements. Theoretically, it should be not less than 2.56 times the maximum frequency to be expected in the signal or the highest frequency of interest, provided suitable anti-aliasing filters are used before sampling.

In practice, it is advisable to provide for a sampling rate at least two times higher than the theoretical limit.

The maximum overall sampling rate of the system is limited by the maximum scanning rate and/or the time required for A/D conversion.

8.3.4 If phase comparison between different channels is required (see **9.2.5**), proper measures should be taken to ensure the possibility either of correct relative time reference between the channels concerned or of compensating — if possible — for any time lag introduced by sequential scanning of the channels.

9 Data acquisition and processing

9.1 General

The level of vibration and pulsation of a hydraulic machine is assessed from the results of vibration and pulsation measurements taken at the locations specified in **5.2** and processed as specified below.

The processing should be accomplished for each steady state operating point mentioned in **4.1**. For transients, the data should be processed so that no significant peak values are overlooked.

The quality of a machine can then be estimated by comparing the vibration or pulsation test results with those for other machines of the same type and size — as classified according to **2.4** — or with “quality assessment” curves or tables, if such curves or tables are available for this hydraulic machine type (see clause **3**).

An adequate estimation of quality can be ensured provided that during tests all elements of the vibration measuring system have operated within their respective operating range and repeatability of test results has been checked wherever possible.

The first direct assessment of the nature of vibration which is based on raw data can be accomplished by visualizing the measured vibration quantities “on line” or “off line”, e.g. on the display screen of an oscilloscope with time-dependent X-axis or in the X – Y mode of operation (Lissajous’ figures). It is recommended to store the observation on a permanent medium (e.g. photographs or computer print-outs). See clause **8** for more detail on recording.

A better understanding of the vibration or pulsation phenomena can be obtained from further processing of the data. The process of evaluation consists of manually or automatically measuring and counting amplitudes and respective frequencies.

Usually the variation of vibration and pulsation levels with time is recorded and the results are presented as a function of time on a linear or logarithmic scale.

This method is fast and especially convenient in cases where instantaneous values are of no interest.

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For numerical representation and comparison with some reference, special parameters are found by further processing of data or by digital data acquisition and processing, if sufficiently high sampling rates can be ensured.

In cases where determination of some vector or tensor values is needed for adequate understanding of the nature of vibration (or pulsation), manual or computer-aided calculations become necessary.

For instance, Appendix A deals with the computation of instantaneous principal stress magnitudes and directions based on the strain measurements accomplished by means of strain gauge "rosettes".

Since special care has to be exercised to obtain reliable results in the determination of such compound values and, since this kind of evaluation is feasible only with an efficient EDP system, one should confine oneself to what is indispensable.

9.2 Selection of data processing methods

Experience of vibration and pulsation measurement in hydraulic machines has shown that the oscillating signal in question can be treated as the sum of two types of oscillations:

- — periodic oscillations (related e.g. to rotational, blade, processing vortex, and other frequencies), and
- — random oscillations.

For steady-state operating conditions this sum of oscillations can be considered as a stationary random process.

The processing of the measured data essentially depends on the chosen method of measurement and the purpose of the test.

Commonly used are the following data processing methods:

1) Peak-to-peak or peak value analysis.
2) Effective value analysis.
3) Statistical processing of data.
4) Power density spectral analysis.
5) Complete spectral analysis, including phase analysis.

9.2.1 *Peak-to-peak or peak value analysis*

The peak-to-peak values or the peak values of vibrations and pulsations are investigated to provide an indication of the level of the vibrations or pulsations at a given measuring point. These types of analysis are very often made for vibration or pulsation tests. In this kind of analysis only amplitude values are considered while frequencies are disregarded. The methods are fast and especially convenient in cases where peak values are constant or vary slightly with time and all other instantaneous values are of no interest.

The peak-to-peak analysis employs time-frames to see how the short-term maximum excursion of an oscillating quantity varies with time. Within each time-frame the absolute maximum excursion ΔX_{pp} (from minimum to maximum peak) of the oscillating quantity is measured and recorded in a suitable way.

The time-frame method should also be used in peak value analysis. For this type of analysis the absolute value of the maximum deviation from the mean value of the oscillating quantity is measured and recorded. In the case of an oscillation which is totally symmetric about the mean value, the peak value ΔX_p is equal to

$\frac{\Delta X_{pp}}{2}$, i.e. half of the peak-to-peak value.

Two different procedures are suggested for the peak-to-peak or the peak value analysis:

- — one, more suitable for transient operation of the machine, where the time-frame may sometimes be enlarged to include the full length of the record;
- — the other, more suitable for records obtained during steady-state operation of the machine, where the overall time of the test record is subdivided into successive time-frames, each time-frame containing a few individual excursions or peak values of the recorded variable.

It is recommended that the results of the above analysis be presented either in the form of a histogram of the peak-to-peak values or the peak values versus the progressive numbers of the successive time frames or in the form of a table.

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The above-mentioned histogram or table can sometimes indicate whether the oscillatory process is essentially random or whether it can be treated as periodic.

In cases where repetitive sharp peaks ("spikes") are characteristic of the oscillatory process the average value of the peak-to-peak values or the peak values over a certain number of time-frames, each containing at least one sharp peak, should be calculated to serve as a measure of the general level of the vibration or pulsation.

The average value for sharp peaks or otherwise the results presented in the histogram or the table may provide an answer to the question of whether the oscillatory process at this measuring location should be analysed more comprehensively or whether the analysis already done will suffice.

Whether peak-to-peak analysis or peak value analysis is most suitable for the investigation of the vibrations or pulsations has to be decided from the nature of the measured variable and the purpose of the measurement.

In many cases it is also necessary to determine the mean value (see **2.3.3.1**) of the measured variable and/or the physical values of the maximum and minimum measured.

The simplest instrumentation for these types of analyses consists of a measuring device capable of indicating peak-to-peak value or peak value of the signal (see Figure 4).

The method of performing the analysis depends on the recording system used if the analysis is not done on-line.

For strip-chart type recordings, the analysis will be carried out manually, measuring the upper and lower extreme values in an adequate time-frame. In the case of magnetic tape recordings, two peak voltmeters, one for maximum peaks and one for minimum peaks are used for peak-to-peak analysis. For peak-value analysis, one peak voltmeter measuring absolute values with compensation of the mean value or a special instrument can be used.

For digital data acquisition and storage a suitable computer program can be used for these evaluations.

9.2.2 *Effective value analysis*

The effective values used in this sub-clause are the ones referred to the mean as defined in **2.3.3.2** (also called standard deviation).

The peak-to-peak value analysis is insufficient in cases where the oscillating process is essentially random in nature (the general level of vibration substantially changes with time, irregular sharp peaks are occurring). Since in such cases the energy contained in the process may be a critical parameter for the assessment of the vibration severity, the effective value analysis should apply.

The results of the effective value analysis should be presented in a tabular form where levels of effective magnitude (displacement, velocity or acceleration for vibration; pressure or strain, etc.) should appear.

If the investigated oscillating process is non-stationary (for instance during transient operation), it should preferably be recorded on a magnetic tape or in digital storage. The record is displayed and investigated visually. Then the record is divided into time-frames where the signal can be treated as a stationary random signal, in a way similar to that already explained for peak-to-peak value analysis (see **9.2.1**). These partial records are then analysed[22] so as to derive effective values over time intervals suitable to the characteristics of each partial record.

9.2.3 *Statistical processing of data*

For steady-state operation of a hydraulic machine where the peak-to-peak value analysis indicates that the oscillatory process is essentially random, it may be convenient to use the concept of probability density for a comprehensive description of the vibrations or pulsations and for the estimation of the severity of vibration or pulsation.

The probability density is defined as the probability of finding instantaneous values of the oscillating quantity within a certain amplitude interval ΔX, divided by the size of that interval (i.e. density).

---

[22] The method of effective-value analysis depends on the recording system used. Strip-chart recordings are not suitable for this type of evaluation. For magnetic tape recordings an r.m.s, voltmeter or special instrumentation can be used. For digital data acquisition and storage suitable computer programs are used.

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The probability density at some specified amplitude level, X, is:

$$\lim_{\Delta x \to 0} \frac{P(X) - P(X + \Delta X)}{\Delta X}$$

Here $P(X)$ is the probability of occurrence of instantaneous values exceeding the level X and $P(X + \Delta X)$ is the probability of occurrence of instantaneous values exceeding the level $X + \Delta X$.

By plotting the value of probability density for all values of X a probability density curve is obtained which has the feature that integration of the curve from a value X_1 to a value X_2 gives the probability of occurrence of instantaneous amplitude values within the interval $(X_2 - X_1)$ directly.

The statistical distribution of maximum vibration or pulsation amplitudes (peaks) can be similarly described by means of the peak probability density curve which shows the probability of occurrence of peaks within small amplitude "windows" at a given level X of the oscillating quantity.

In practice, the probability density curve can be obtained by means of a probability density analogue or digital analyser which measures the time periods during which the signal is found within different amplitude windows.

To obtain the peak probability density curve, the analyser is switched to count the number of peaks falling within different amplitude windows.

The curves are recorded by means of a suitable signal level recorder.

Though probability density data give little or no information as to the time history or frequency content of the process being studied, they are very useful descriptions of the signal and are used for estimations of the oscillatory load.

9.2.4 *Power density spectral analysis*

The processing of measured vibration and pulsation data — especially for tests under steady state conditions — has the ultimate goal of obtaining a comprehensive analysis for component frequencies. A good spectral analysis of vibration can include simultaneous presentation of vibration displacements, velocities and accelerations versus frequency, e.g. in the form of a graph plotted using logarithmic coordinates.

Spectral analysis can be effected on the signal according to two different techniques:

- — spectral power density analysis (either with analog or digital analysers);
- — fast Fourier transform analysis (with digital analysers).

Only in the last case is phase information preserved.

For obtaining the results of spectral analysis in the form of spectral power density, different types of frequency analysers can be used, for instance constant absolute pass bandwidth analyser and constant relative pass bandwidth analyser[23].

The frequency range of the analyser should cover the investigated range (f_L, f_U). When the lower limit of the analyser frequency range is higher than the lower limit of the investigated range, the process may be recorded by means of a magnetic tape recorder suitable for the recording of low frequency oscillations at low tape speed. Then the record is played back at a higher tape speed and the process is analyzed by the available analyser.

The constant relative pass bandwidth analysers should preferably be used for the treatment of low frequency signals as they generally provide higher selectivity in the low frequency range.

When a tape record is used for subsequent data processing, a real-time analyser which can display the spectrum is convenient for use.

---

[23] If a constant absolute pass bandwith analyser is used the resultant power frequency spectrum is directly proportional to spectral power density. When employing a constant relative pass bandwidth analyser, the frequency correction:

$$G(f) = \frac{G_r(f)}{f}$$

should be applied to the spectrum value $G_r(f)$ obtained by means of the analyser in order to get correct power spectral density $G(f)$ (see **2.3.4.7**). This correction is introduced graphically or electrically by means of a special filter.

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9.2.5 *Complete spectral analysis, including phase analysis*

Spectral analysis provides information about the distribution of the energy of the process among the different frequencies (see **9.2.4**). It is sometimes also desired to investigate by this means the relation between two different oscillating quantities.

However, if only the power spectral density at every given frequency is derived, as in simple power density spectral analysis (**9.2.4**), a part of the information content of the signal is lost.

Without knowledge of the phase of each component, indeed, it is not possible to reconstruct from the spectrum the original time-history of the signal(s); we also lose information useful for judging possible linkage of components of different variables at the same frequency.

Complete information (hence the possibility, in principle, to effect the inverse passage from the frequency-domain description to the time-history of the signal(s), and the possibility to look for phase relationship between components of different signals at the same frequency) is preserved by effecting the complete spectral analysis, including "phase analysis". For every frequency f, in this case, not only a density $W(f)$ is derived, but also a phase $\varphi(f)$.

The spectral density at a given frequency can thus be regarded as a complex, or a "vector", quantity[24]:

$$\vec{W}(f) = \{W(f) \cos \varphi\ (f),\ W(f) \sin \varphi\ (f)\}$$

This information can be obtained from the signal(s) either using analogue devices with filters, multipliers and integrating devices, or by digital processing of the signal(s) (FFT: Fast Fourier Transform). This kind of digital treatment can introduce biases or smearing in the spectrum, which can be misleading if not correctly interpreted.

One can obtain $\vec{W}(f)$ for a single signal (spectral density) or for two signals (cross spectral density).

Of course the phases $\varphi(f)$ have only a relative — and not an absolute — meaning.

10 Measurement uncertainties

Prior to evaluation, especially prior to automatically performed evaluation, one has to make sure, e.g. by visual checking of graphical recording, that the recordings are free from disturbances. In the case of disturbances (e.g. "spikes" caused by electromagnetic interference) automatic evaluation is difficult to perform and manual evaluation has to be carried out with special care.

10.1 The uncertainties in measurement of all the time-varying quantities have to be evaluated on the basis of the calibration curves directly determined or provided by the manufacturer, taking into consideration the features of transducers, amplifiers, filters, recorders, data processing units, etc.

10.2 The uncertainties in measurement of the quantities describing operating conditions (specific hydraulic energy, power, guide vane (needle) opening, runner blade angle, net positive suction specific energy) are calculated according to IEC Publication 000[25].

10.3 The acceptability of measurement uncertainties, confirmed by the examples of oscillograms or in some other way, should be agreed with the concerned parties, with a view to ensuring that there is consistency between: rating of the instrument, quality of calibration, maximum expected inaccuracy of measuring channel and admissible limits of the vibrations or pulsations to be evaluated, if specified.

10.4 Relative uncertainties in special parameters to be used in evaluation should be computed from relative errors of physical quantities involved in their mathematical definition according to the usual rules of error theory.

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[24] The spectral density $G(f)$ derived in the simple spectral analysis of one single signal (**9.2.4**) is coincident with the modulus of the density amplitude $\vec{W}(f)$, i.e. $G(f) = |W(f)|$.
It is sometimes of advantage to consider that $\vec{W}(f)$ is the Fourier transform of the correlation function (auto-correlation function for a single signal, cross-correlation function for two signals). The two descriptions are thus equivalent.

[25] At present Document 4 (Central Office) 48.

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11 Final report

The final report (see Appendix C) shall contain, but not necessarily in this order, the following indications:

a) object of tests and identification of main data of the machine;

b) test programme and preliminary agreements pertinent to the tests;

c) personnel taking part in the tests;

d) test conditions (specific hydraulic energy, generator or motor power, NPSE, opening of guide vanes or of needles, angle of runner blades, rotational speed, etc.);

e) description of instrumentation with indication of manufacturer, type, serial number, calibration coefficient, description of test procedure and data processing;

f) description of transducer locations given in written and in graphic form; indication of the locations on an overall drawing of the machine;

g) diagrams used during data processing (calibration and others);

h) test results in the form of text, tables and diagrams, examples of records;

i) statement as to inaccuracy of measurement;

j) conclusions and recommendations.

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Appendix A Formulae for calculating principal stresses and signal processing for dynamic strain measurements with rosettes

A.1 Formulae for calculating principal stresses

The principal stresses are not obtained directly but calculated from measured strains. Under different stress conditions, the formulae to use are:

A.1.1 *For uniaxial stress condition*

$$\sigma_0 = E \cdot \varepsilon_0$$

where:

σ_0 = calculated stress
E = Young's modulus
ε_0 = measured strain

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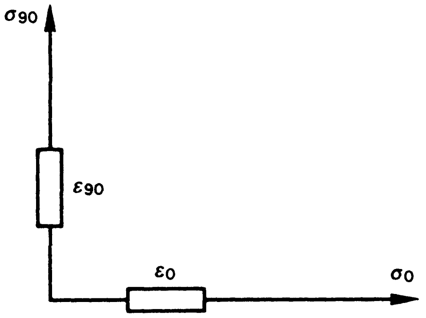
A.1.2 *For plane stress condition when directions of principal stresses are known*

$$\sigma_0 = \frac{E}{1 - \nu^2}(\varepsilon_0 + \nu\varepsilon_{90})$$

$$\sigma_{90} = \frac{E}{1 - \nu^2}(\varepsilon_{90} + \nu\varepsilon_0)$$



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where:

ν = Poisson's ratio

A.1.3 *For plane stress condition when directions of principal stresses are unknown*

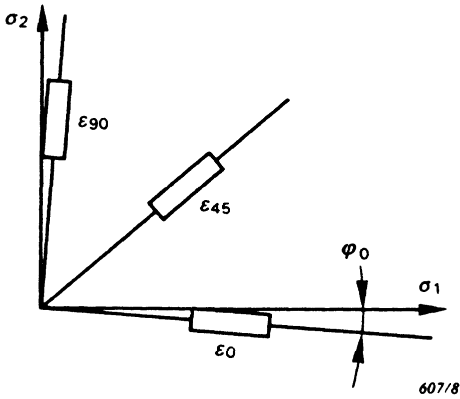
In this case "rosettes" of three gauges must be installed at the investigated point. Different types of "rosettes" (45°, 60°, 120°) are available and the corresponding formulae are:

A.1.3.1 *45° rosettes*

$$\operatorname{tg} 2\varphi_0 = \frac{2\varepsilon_{45} - (\varepsilon_0 + \varepsilon_{90})}{\varepsilon_0 - \varepsilon_{90}}$$

$$\sigma_{1,2} = \frac{E}{1 - \nu} \cdot \frac{\varepsilon_0 + \varepsilon_{90}}{2} \pm \frac{E}{1 + \nu} \cdot \frac{\varepsilon_0 - \varepsilon_{90}}{2\cos 2\varphi_0} =$$

$$= \frac{E}{1 - \nu} \cdot \frac{\varepsilon_0 + \varepsilon_{90}}{2} \pm \frac{E}{1 + \nu} \cdot \frac{\sqrt{2}}{2}\sqrt{(\varepsilon_0 - \varepsilon_{45})^2 + (\varepsilon_{45} - \varepsilon_{90})^2}$$



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where:

φ_0 = algebraic angle between the axis of the gauge at 0° and the direction of maximum stress σ_1
σ_1 = maximum principal stress
σ_2 = minimum principal stress

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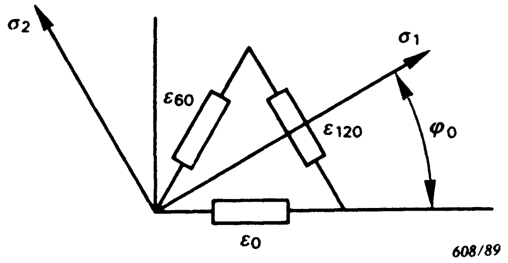
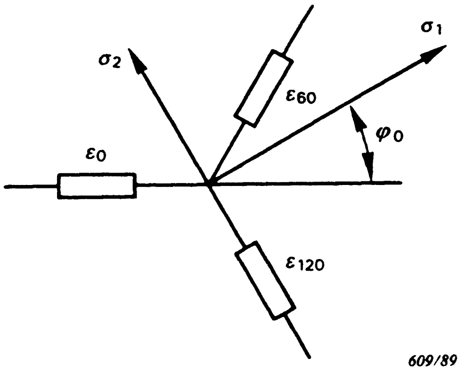
A.1.3.2 *60° rosettes and 120° rosettes*





$$\tan 2\varphi_0 = \frac{\sqrt{3}\,(\varepsilon_{60} - \varepsilon_{120})}{2\,\varepsilon_0 - (\varepsilon_{60} + \varepsilon_{120})}$$

$$\sigma_{1,2} = \frac{E}{1-\nu} \cdot \frac{\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120}}{3} \pm \frac{E}{1+\nu} \cdot \frac{\sqrt{2}}{3} \cdot \sqrt{(\varepsilon_0 - \varepsilon_{60})^2 + (\varepsilon_{60} - \varepsilon_{120})^2 + (\varepsilon_{120} - \varepsilon_0)^2} =$$

$$= \frac{E}{1-\nu} \cdot \frac{\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120}}{3} \pm \frac{E}{1+\nu} \cdot \frac{2\varepsilon_0 - (\varepsilon_{60} + \varepsilon_{120})}{3 \cos 2\,\varphi_0}$$

A.2 Signal processing for dynamic strain measurements with rosettes

The signal processing for dynamic strain gauge measurements with rosettes can be done in two principal ways using the following methods:

— processing the analogue signals on an analogue computer;

— parallel sampling and A/D conversion of the signals from the three signals of each rosette. Processing of the data on a digital computer.

A.2.1 *Analogue method*

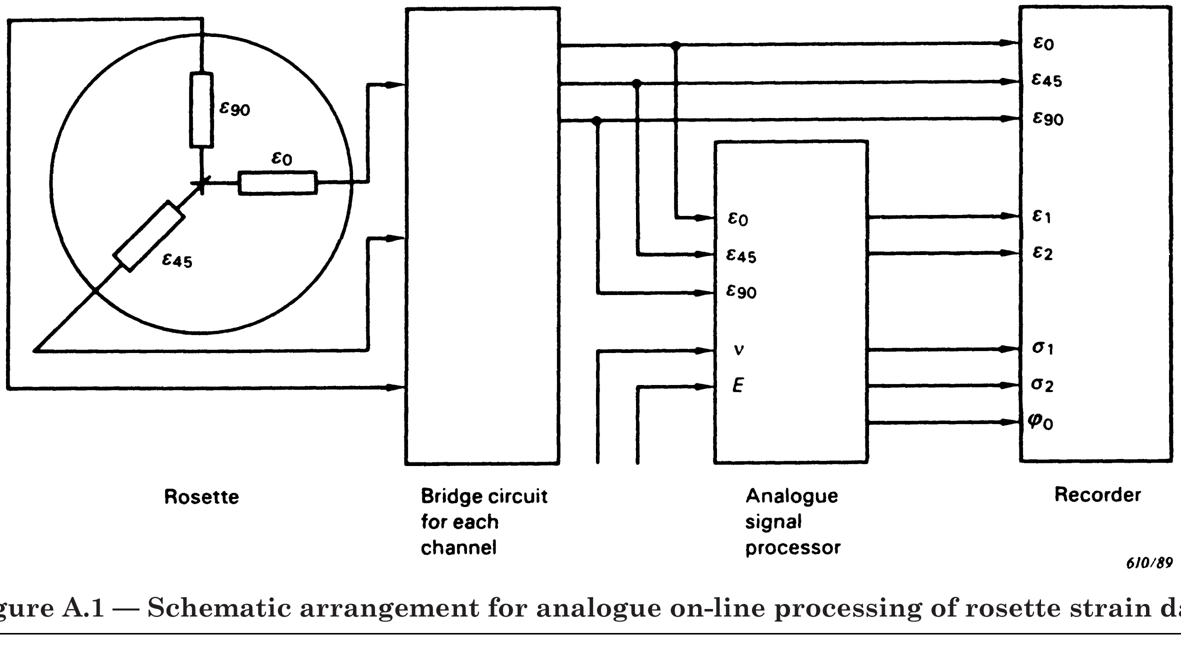


Figure A.1 — Schematic arrangement for analogue on-line processing of rosette strain data

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Figure A.1 is a diagram of an arrangement for the analogue processing of the strain signals of a rosette. The analogue computer has to be able to carry out the operations corresponding to the formulae given in **A.1.3**.

The maximum analysed frequency (in case of on-line processing) is limited by the speed of the signal processor and the signal-conditioning equipment.

In the figure, provisions in the measurement chain for storage and display of the transducer signal (see Figure 4, clause **6**) are not shown.

A.2.2 *Digital method*

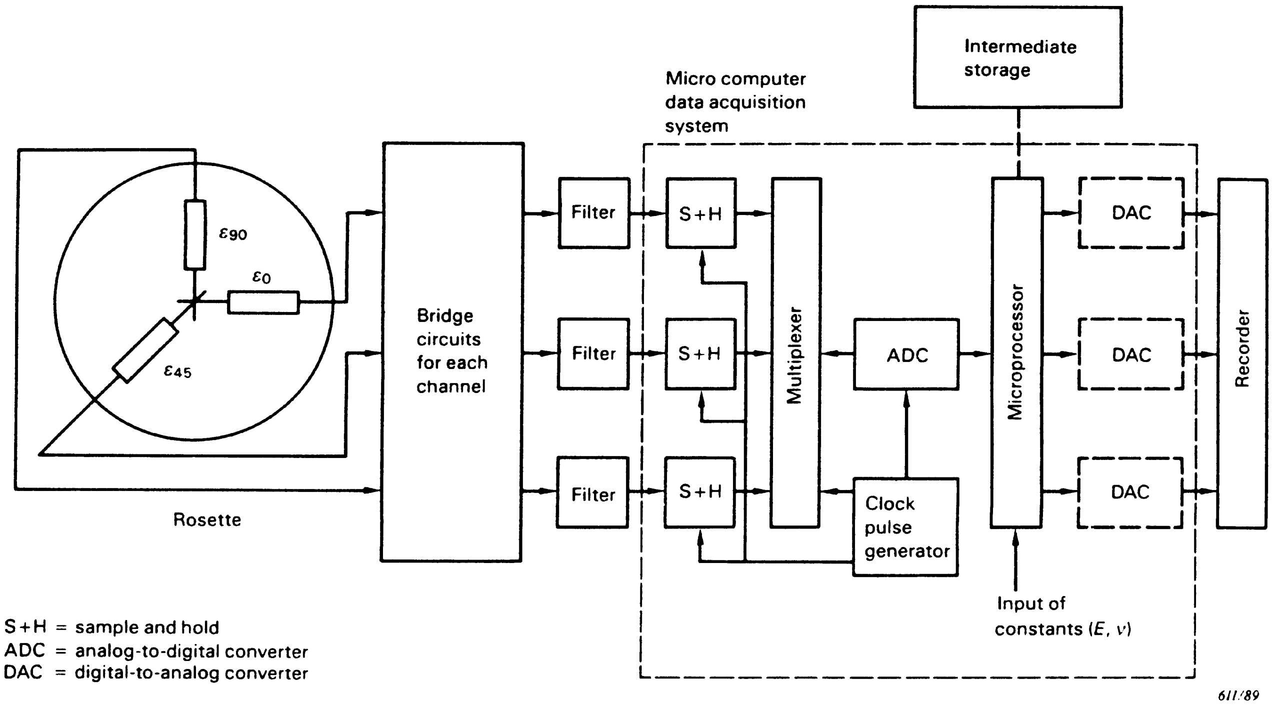

Figure A.2 — Schematic arrangement of digital on-line processing of rosette strain data

Figure A.2 shows schematically an arrangement for the digital processing of the strain signals of a rosette. The sampling rate and subsequently the maximum frequency of the signals is limited (in the case of on-line processing) by the speed of the processor. An exactly simultaneous sampling of the channels is necessary. Analogue low-pass-filters are needed to avoid aliasing errors.

The result of this processing, either analogue (Figure A.1) or digital (Figure A.2) is the instantaneous values of σ_1 and σ_2 and their instantaneous orientation φ_0; according to the use intended for these quantities, further processing may be needed.

Appendix B Formulae for calculating the torque on a cylindrical solid shaft and the axial load on a rectangular or circular section link using the strain gauge technique

As said before in **7.2.4** and **7.2.7**, the direct calibration of the machine parts (shaft, stem or link of a guide vane) on which the strain gauges for torque and axial load measurements are installed, is sometimes impossible.

In this case, one can apply to a first approximation the theoretical formulae (see below) in order to obtain an evaluation of the magnitude to be measured on the basis of the total unbalance of the strain gauge bridge utilized.

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B.1 Torque on a solid shaft of cylindrical cross-section

With reference to Figure B.1, the total unbalance of the measurement strain gauge bridge supplies a strain value $\Sigma\,\varepsilon_{45}$ four times higher than the value ε_{45} of the single strain gauge, applied at 45° with respect to the axis on the outer surface of the shaft.

From the well known relations:

$$\tau = \frac{2M_t}{\pi\left(\frac{D}{2}\right)^3}$$

$$\gamma = \frac{\tau}{G}$$

$$\varepsilon = \frac{\gamma}{2}$$

we obtain:

$$M_t = \pi\left(\frac{D}{2}\right)^3 G\frac{\Sigma\,\varepsilon_{45°}}{4},$$

from which M_t can be obtained.

B.2 Axial load on a link with rectangular or cylindrical cross-section

With reference to Figure B.2, the total unbalance of the measurement strain gauge bridge $\Sigma\,\varepsilon$ supplies a strain value 2 $(1 + \nu)$ times higher than the value ε_1 of the single strain gauge, applied axially on the outer surface of the link considered.

From the well known formulae:

$$\sigma_1 = \frac{P}{A}$$

$$\sigma_2 = 0$$

$$\varepsilon_1 = \frac{\sigma_1 - \nu\sigma_2}{E} = \frac{\sigma_1}{E}$$

$$\varepsilon_2 = \frac{\sigma_1 - \nu\sigma_1}{E} = \frac{\nu\sigma_1}{E}$$

the total unbalance of the strain gauge bridge is obtained:

$$\Sigma\,\varepsilon = \frac{\sigma_1}{E}2(1+\nu) = 2(1+\nu)\,\varepsilon_1$$

from which:

$$P = A\,\sigma_1 = \frac{A\,E\,\Sigma\,\varepsilon}{2(1+\nu)}$$

The symbols have the following meanings:

τ = shear stress;

M_t = shaft torque;

D = shaft diameter;

γ = angular shear distorsion;

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G = shear modulus: $G = \dfrac{E}{2(1+\nu)}$;

ε = strain (ε_1 and ε = principal strains);

σ = normal stress (σ_1 and σ_2 = principal stresses);

E = Young's modulus;

ν = Poisson's ratio;

A = link cross-sectional area;

P = axial load on the link.

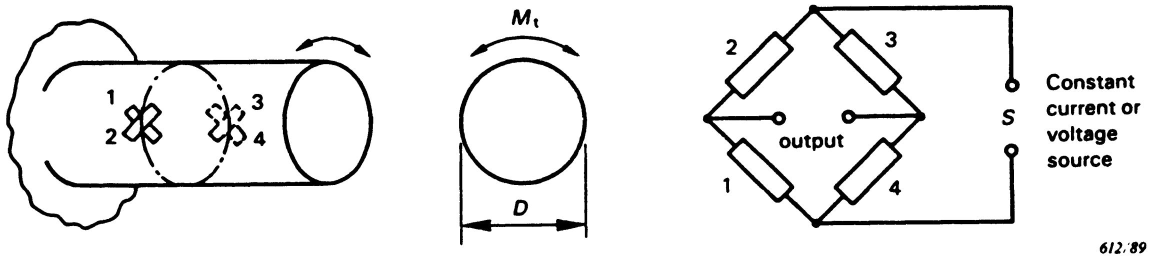

Figure B.1 — Connection of the strain gauges for torque measurement on a cylindrical shaft

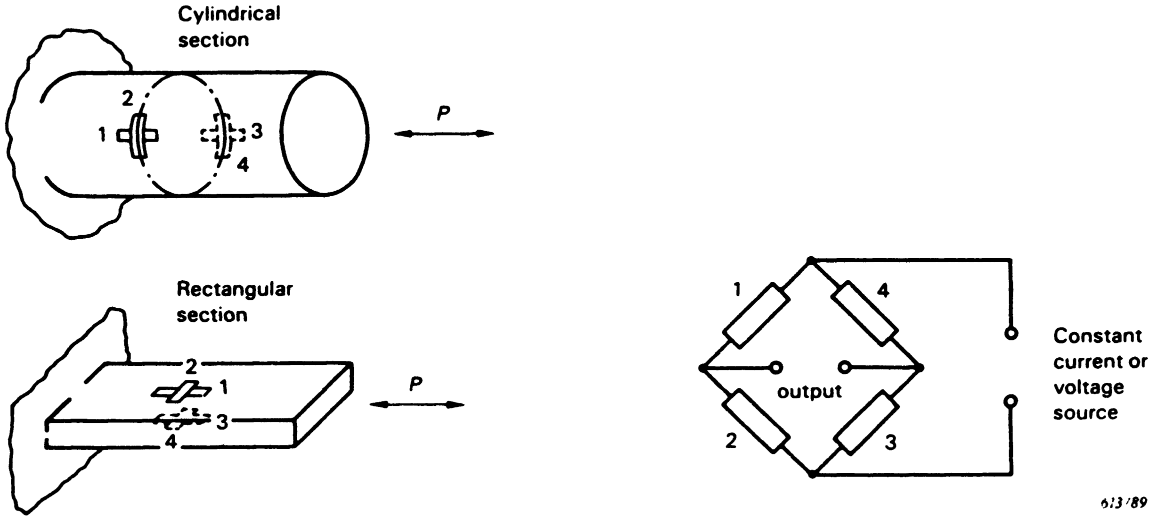

Figure B.2 — Connection of the strain gauges for the axial load measurement on a cylindrical or rectangular section link

Appendix C Example of final report

This appendix gives an example of the possible structure and contents of the final report.

This example is only intended as a guide to preparing the report and by no means should be taken as a fixed form.

C.1 Introduction

Content e.g.:

- — name of the plant;
- — owner of the plant;
- — date of the tests;

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- reason or motivation for the tests;
- very rough description of the measurements;
- organization(s) asking for the measurements;
- organization(s) performing the measurements;
- additional remarks.

C.2 Object of test

Content e.g.:

- description of the whole unit and in particular of the hydraulic machine;
- main technical data;
- copies of general view drawing (if available);
- information concerning maintenance and operation conditions during the tests.

C.3 Test programme

Content e.g.:

- statement of contractual specifications and regulations relevant for the tests;
- statement of all other preliminary agreements pertinent to the tests;
- time schedule for the tests and description of the planned operational modes for the tests.

C.4 Personnel taking part in the tests

Content e.g.:

- name of the chief of tests;
- test crew, number of persons, functions, name of companies;
- name of observers sent by the owner of the plant and/or the contractor.

C.5 Test installations and equipment

Content e.g.:

- list of measured quantities:
- outline drawing with indication of transducer locations:
- description of transducer locations and of transducer mountings in written and in graphic form;
- description of the instrumentation:
  - transducers,
  - amplifiers,
  - recording systems,
  - monitoring systems,
- on-line data processing systems, if used, with indication of the manufacturer, type and, if necessary, serial numbers;
- tabulation of the calibration coefficients and their source;
- description of the calibration procedures if performed in the plant prior to the measurements and/or after the tests;
- schematic block diagrams of the measuring chain (transducers, amplifiers, recording and monitoring systems).

C.6 Test documentation

Content e.g.:

- daily log of the events during the tests;
- tabulation of the tests (as an example see Figure C.1);
- records of the results of provisional evaluations, if performed;
- examples of on-line recorder charts and/or plotted diagrams if on-line data processing is used.

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C.7 Test results

Content e.g.:

- — tabulation of the specific test conditions for all measurements (as an example see Figure C.2);
- — tabulation of the results of all measurements (as example see Figure C.3 and Figure C.4);
- — diagrams (e.g. strip chart recorder or plotter, output) showing one of the measured quantities for several tests (as an example see Figure C.5) or of several quantities for one test (as an example see Figure C.6).

C.8 Evaluation of the test results

Content e.g.:

- — description of the evaluation and calculation methods, and, if used, of the instrumentation for the evaluation, frequency analysers, computers, etc. (schematic block diagrams);
- — sample calculation for one selected test whenever possible, for demonstration;
- — tabulation of the results of the evaluations;
- — diagrams, showing the results of the evaluations, e.g. frequency analyses (as an example see Figure C.7).

C.9 Interpretation of the results

- — discussion of the results;
- — comparison of the results of the evaluation with respect to the different operational conditions of the machine;
- — comparison of the test results with pulsations measured on model (if available).

Any interpretation giving the relations and dependences between exciting and excited quantities, as well as any recommendation about the operation of the machine, are outside the scope of this guide (see **1.3**).

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Table ....: **Main data of tests**

Date:..

Plant:

....

Unit:

....

Operating conditions
of other units:

....

Test No.	**Time**	***P***	$\mathbf{a}_{o}$[c]	**Head-water level** (high pressure)	**Tailwater level** (low pressure)	[a]	**Magnetic tape counter**		**Conditions test/Remarks** (see **4.1.1**)
		MW	% or mm	m (asl)[b]	m (asl)[b]		begin	end	

[a] Additional parameters if necessary, e.g. rotational speed

[b] Elevation above mean sea level

[c] Guide vane (needle) opening

Figure C.1 — Example of a possible list of tests

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Table: **Evaluation of test results**

Date:..

Plant:

....

Unit:

....

Operating conditions of other units:

....

General data of operational conditions during test runs (switchboard meters and additional instruments)

Test No.	***P*** gen./mot.	**Head-water level** (high press.)	**Tail-water level** (low press.)	**Geodetic height of plant**	***P*** turb./pump	**Guide vane** (needle) opening	**Runner blade angle**	**Additional parameters**		**Remarks**
	MW	m asl	m asl	m	MW	% or mm	Degrees			

The additional parameters may be:
- — specific hydraulic energy;
- — discharge;
- — rotational speed;
- — turbine or pump efficiency.

In special cases, the following parameters can be helpful to describe the operational conditions of the machine:
- — ratio of specific hydraulic energy (or head) during measurements to specific hydraulic energy (or head) at efficiency optimum[a];
- — ratio of discharge during measurement to discharge at efficiency optimum[a];
- — ratio of power during measurement to power at efficiency optimum[a];
- — specific hydraulic energy coefficient or speed parameter: $E_{nD} = \frac{E}{n^2 D^2}$ or $n_{ED} = \frac{n\ D}{E^{0.5}}$[b]
- — discharge coefficient: $Q_{nD} = \frac{Q_1}{n\ D^3}$ or $Q_{ED} = \frac{Q_1}{D^2\ E^{0.5}}$[b]
- — cavitation factor $\sigma = NPSE/E$

[a] Values for specific hydraulic energy (or head), discharge and mechanical power at efficiency optimum can be taken from model test results.

[b] E_{nD} (or n_{ED}) and Q_{nD} (or Q_{ED}) and σ may be helpful to compare measurements of hydraulically similar machines. *D* is the reference diameter.

Figure C.2 — Example of a possible list of operational conditions during the tests

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Table: **Results of**...**tests**

Date:...

Vibrations at point No. ....

Description: ....

Plant:

....

Unit:

....

Operating conditions
of other units

....

....

Test No.	*P* Gen./Motor	Vibration variable X^a						Dominant frequency (if any)			Additional parameters[b]		Remarks[c]
		Peak-to-peak or peak			Effective (r.m.s)								
		X_x	X_y	X_z	X_x	X_y	X_z	X_x	X_y	X_z			
	MW							Hz	Hz	Hz			

[a] Vibration variable X: displacement, velocity or acceleration, X_x, X_y, X_z being the cartesian components.

[b] Additional parameters may be for example:

X^a_{xeff} ,X^a_{yeff} ,X^a_{zeff} : effective value of the highest peak in the power-frequency spectrum of the vibration variable X;

$\frac{X^a_{xeff}}{X_{xeff}}, \frac{X^a_{yeff}}{X_{yeff}}, \frac{X^a_{zeff}}{X_{zeff}}$: ratio of effective value of the highest peak in the power-frequency spectrum to the effective value of the vibration variable X.

[c] Specify the frequency range of the analysis.

Figure C.3 — Example of a possible list of test results of vibration measurements

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Table: **Results of**..**tests**

Date:..

Pressure pulsations at point No....

Description:...

Plant:

....

Unit:

....

Operating conditions of other units:

....

Test No.	P Gen./Motor	p_{pp}	$\frac{p_{pp}}{\varrho E}$	$\bar{p}$ [a]	p_{rms}	$\frac{2\sqrt{2}\,p_{eff}}{p_{pp}}$	Dominant frequency	p^{a}_{eff} [b]	$\frac{p^{a}_{eff}}{p_{eff}}$	Additional parameters
										Remarks[c]
	MW	Pa (bar)		Pa (bar)	Pa (bar)		Hz	Pa (bar)		

[a] $\bar{p}$ = stationary mean value.

[b] p^{a}_{eff} = effective value of the highest peak in the spectrum of pressure pulsations.

[c] Specify the frequency range of the analysis.

Figure C.4 — Example of a possible list of test results of pressure pulsation measurements

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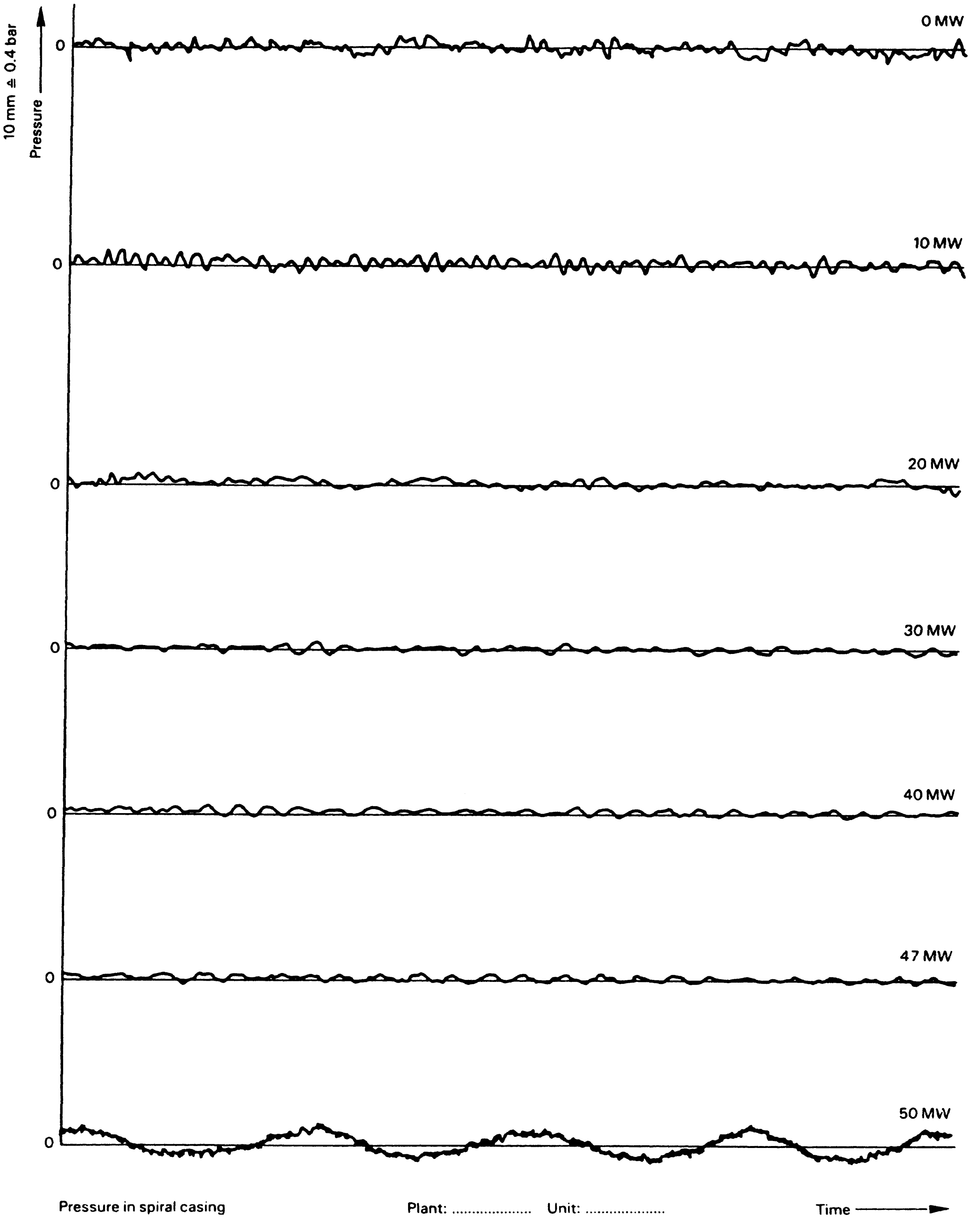

Figure C.5 — Example of a diagram showing one variable for several tests

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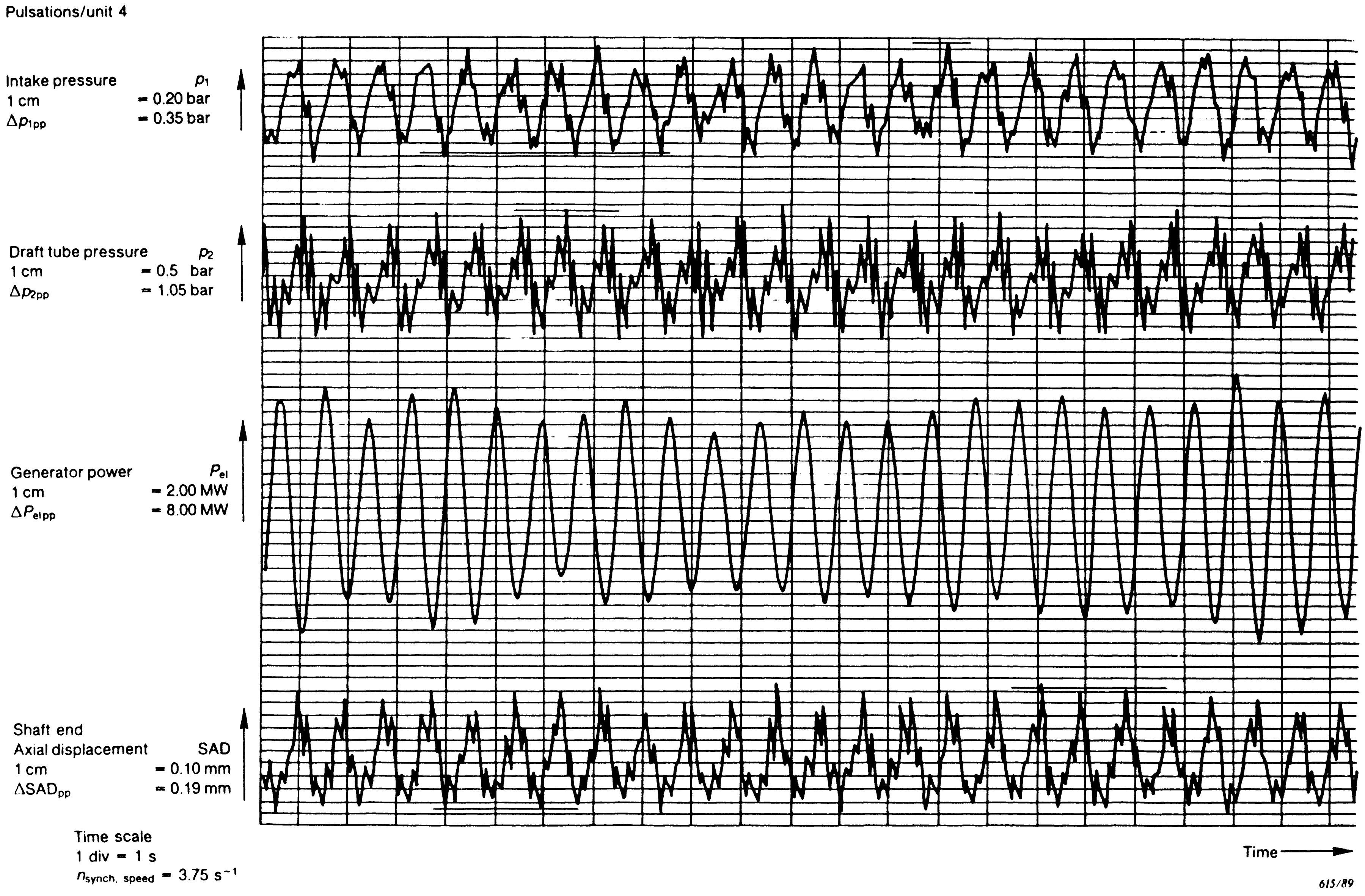

Figure C.6 — Example of a diagram showing several variables for one test

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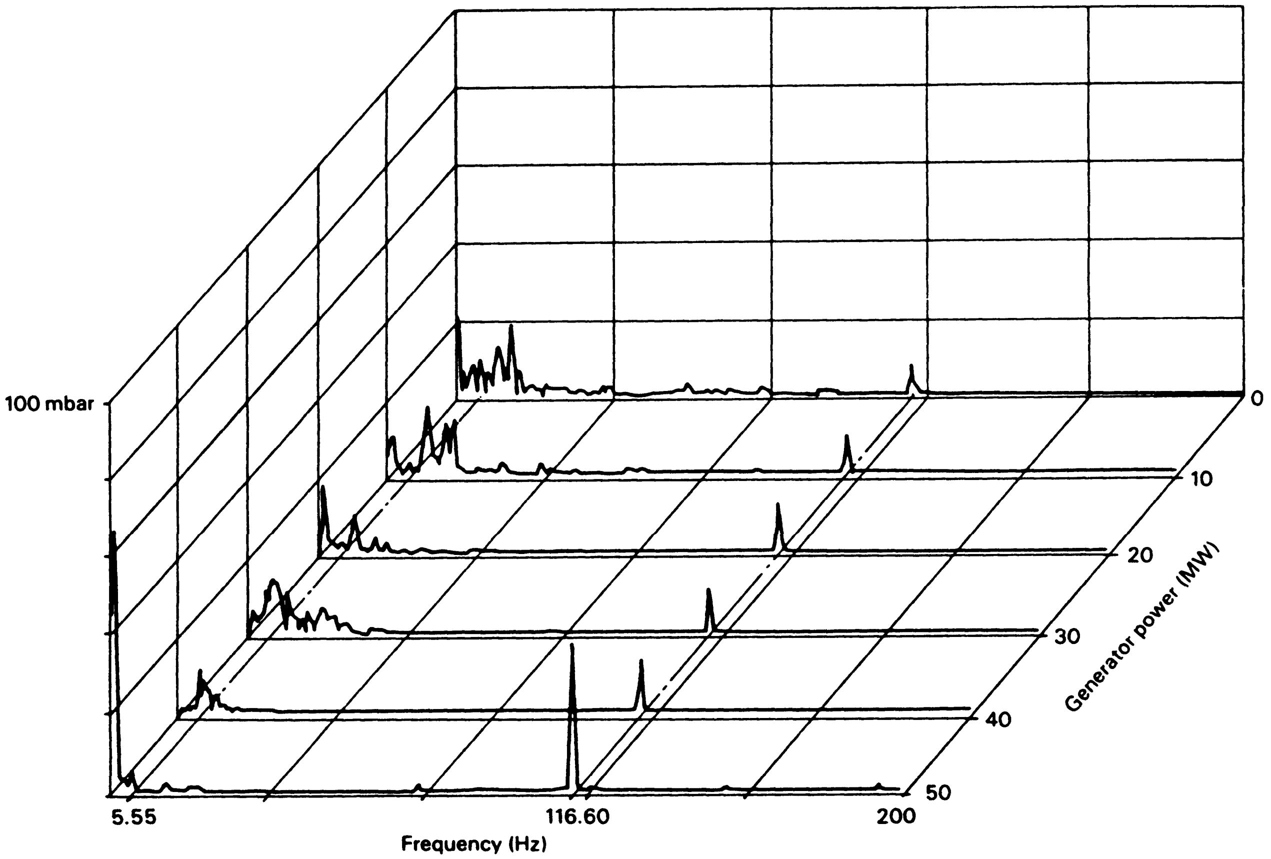

5.55 rev/s = rotational speed
116.60 Hz = 5.55x7x3, rotational speed x number of runner blades (7) x 3rd order (3rd harmonic)

616/89

Figure C.7 — Example of a diagram showing the results of an analysis

Appendix D Distortion of pressure pulsation measurements for transducers mounted with a connecting pipe

If an arrangement as shown in Figure D.1, with connecting pipe and instrument chamber, is adopted, distortion is to be expected in the signal measured by the transducer inside the chamber (*I*) in comparison with the measurement that would be effected at the mouth through which the connecting pipe communicates with the water passage (*II*).

Such distortion becomes particularly severe as the frequency of the signal (starting from zero) reaches a first critical frequency f_c depending on several parameters, including:

— the ratio $\dfrac{V_c}{L_c A_c}$

— the elasticity of the pipe and chamber walls, etc.

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For instance, in the particularly simple case of rigid walls and no gas bubbles in the system, it can be shown (under the assumptions of negligible damping, small amplitude pulsations and pipe diameter small as compared with a_c/f_c) that the first critical frequency f_c is given by the formula:

$$\operatorname{cotg} \frac{2\pi f_c L_c}{a_c} = \frac{2\pi f_c V_c}{a_c A_c}$$

where a_c is the wave propagation velocity in the connecting pipe (see **2.3.4.12**);

or, for $V_c \ll A_c L_c$:

$$f_c = \frac{a_c}{4 L_c} \cdot \frac{1}{1 + \frac{V_c}{L_c A_c}}$$

In practice, it is advisable to avoid operation of measuring equipment above 0.1 f_c and envisage the use of suitable low-pass filters.

Further distortion is introduced by any air or vapour bubbles present in the system. Particular care should therefore be devoted to mounting, filling and purging of the system.

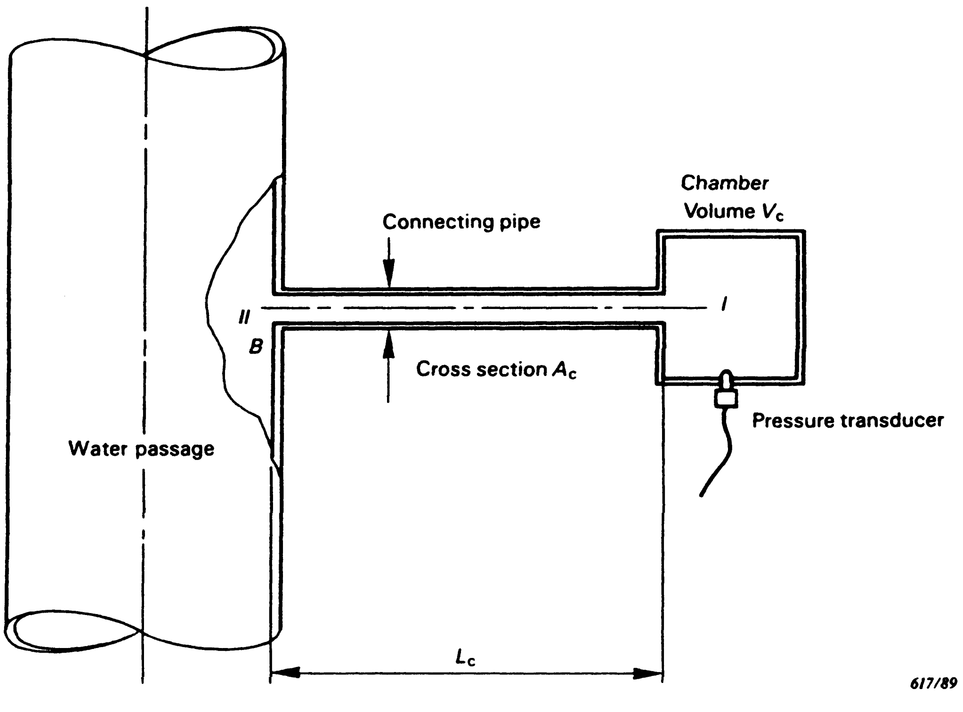

Figure D.1 — Schematic arrangement of pressure transducer mounted with connecting pipe

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Annex ZA (normative)
Other international publications quoted in this standard with the references of the relevant European publications

When the international publication has been modified by CENELEC common modifications, indicated by (mod), the relevant EN/HD applies.

IEC Publication	Date	Title	EN/HD	Date
184	1965	*Methods for specifying the characteristics of electro-mechanical transducers for shock and vibration measurement*	HD 178 S1	1977
222	1966	*Methods for specifying the characteristics of auxiliary equipment for shock and vibration measurements*	—	—

Other publications quoted:

ISO 2041:1975	*Vibration and shock — Vocabulary — Bilingual edition*
ISO 3945:1985	*Mechanical vibration of large rotating machines with speed range from 10 to 200 tr/s — Measurement and evaluation of vibration severity in situ*
ISO 5347-0:1987	*Methods for the calibration of vibration and shock pick-ups* Part 0: *Basic concepts*
ISO 5348:1987	*Mechanical vibration and shock — Mechanical mounting of accelerometers*
ISO 7919-1:1986	*Mechanical vibration of non-reciprocating machines* *Measurements on rotating shafts and evaluation* Part 1: *General guidelines*
ISO 8042:1988	*Shock and vibration measurements — Characteristics to be specified for seismic pick-ups*

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Association of Consulting Engineers
Department of Trade and Industry (National Engineering Laboratory)
Electricity Supply Industry in England and Wales
Institution of Civil Engineers
Institution of Electrical Engineers
North of Scotland Hydro-electric Board
Power Generation Association (BEAMA Ltd.)
University of Southampton

National annex NB (informative) Cross-references

Publication referred to	**Corresponding British Standard**
ISO 5347-0:1987	BS 6955 *Calibration of vibration and shock pick-ups* Part 0:1988 *Guide to basic principles*
ISO 5348:1987	BS 7129:1989 *Recommendations for mechanical mounting of accelerometers for measuring mechanical vibration and shock*
ISO 7919-1:1986	BS 6749 *Measurements and evaluation of vibration on rotating shafts* Part 1:1986 *Guide to general principles*
ISO 8042:1988	BS 7119:1989 *Specification for shock and vibration measurements: characteristics to be specified for seismic pick-ups*

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