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Ultrasonics – Piezoceramic transducers –

Characteristics and measurement methods

Note: This document is intended as a revision to Technical Report 1088. It is purposefully conformed to match the format and characteristics of IEC 61985 Ed. 1.0 Ultrasonics – Resonant and non-resonant magnetostrictive transducers – Characterization and measurement of performance (Stage A2 CD)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

Ultrasonics – Piezoceramic transducers –

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FOREWORD

General part – to be supplied by Central Office of IEC.

Specific part – to be supplied by committee secretariat.

Introduction

This Standard is applicable to longitudinally vibrating, resonant, prestessed piezoceramic ultrasonic transducers. Such transducers are designed for producing sonic or ultrasonic power in liquid, solid or gaseous media for the purpose of various forms of ultrasonic processing that may include industrial, chemical, biological, and medical applications. The operation of such transducers, and hence the acoustic output, may be continuous (e.g hours or days in chemical processing) or intermittent (e.g. welding).

The Standard specifies the essential electro-acoustical performance characteristics for such transducers, and their methods of measurement.

1 Scope

This Standard is applicable to longitudinally vibrating, resonant, prestessed piezoceramic ultrasonic transducers **(referred to as "transducers" hereafter)** designed for producing sonic or ultrasonic power in liquid, solid or gaseous media, either in a continuous or intermittent mode of operation. The Standard specifies the essential electro-acoustical performance characteristics for such transducers, and their methods of measurement.

2 Normative references

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

Provisional list of applicable standards.

IEC 27: Letter symbols to be used in electrical technology.

IEC 50(801): International Electrotechnical Vocabulary, Chapter 801, Acoustics and electroacoustics.

3 Classification of transducer measurements

Measurements will be classified under the following categories.

3.1 Unloaded under free - free conditions.
3.2 Loaded with power input, propagation into liquids or gases.
3.3 Loaded with power input, propagation into solids.

4 Definitions and symbols

For the purposes of this Standard, the following definition of "transducer" applies.

Transducer. Shall designate a longitudinally vibrating, resonant assembly consisting of piezoceramic disks/rings located between end masses, the disks/rings being under prestress from single or multiple bolts, or other equivalent means, such as a tension shell. Such transducers, when attached to appropriate wave guides, horns, containers, or other such coupling means, are be used to transmit energy into solid, liquid or gaseous loads for applications that include, as examples, welding, drilling, forming, grain refinement, chemical processing, surgery, cell disruption, surface hardening, cleaning, and defoaming.

Other symbols, terms and definitions are as follows:

P_e	= electrical input power
V_T	= transducer drive voltage
I_T	= transducer drive current
ϕ	= phase shift between V_T and I_T
P_a	= transducer acoustic output power
P_d	= transducer magnetic power loss
P_{ml}	= transducer internal mechanical power loss
P_m	= transducer total mechanical output power
η_{ea}	= electro-acoustic efficiency
η_{em}	= electro-mechanical efficiency
η_{ma}	= mechano-acoustic efficiency
ξ	= vibration displacement amplitude
f_{res}	= frequency of resonance
f_r	= transducer series resonant frequency
f_a	= transducer anti-resonant frequency
Δf	= bandwidth
Q	= mechanical quality factor
Z	= transducer electrical impedance
R	= real component of the electrical impedance
X	= imaginary component of the electrical impedance
Z_{res}	= value of the electrical impedance at the frequency of resonance
Z_a	= transducer blocked electrical impedance
R_s	= resistor connected in series with the transducer
σ	= mechanical stress
σ_0	= mechanical pre-stress
Y	= modulus of elasticity
k	= electromechanical coupling factor
v	= vibration velocity amplitude (ω x ξ)

5 Essential characteristics

(The following essential characteristics are nominated for discussion)

The essential performance characteristics of resonant, prestressed, piezoeceramic ultrasonic transducers are:

- Input electrical power
- Acoustical output power and electro-acoustical efficiency
- Vibrational displacement amplitude
- Frequency of resonance of the transducer
- Bandwidth and mechanical quality factor
- Electrical impedance of the transducer at resonance
- Blocked (damped) electrical impedance of the transducer

6 Definition of characteristics

(NOTE: For consideration: continuous, intermittent operation performance parameters)

6.1 Input electrical power P_e

With sinusoidal excitation the a.c. power P_e consumed by the transducer from the power supply may be expressed as:

$$P_e = V_T I_T \cos\phi \tag{1}$$

where V_T is the driving voltage at the transducer terminals, I_T the current flowing to the transducer and ϕ is the phase shift angle between the voltage and current.

(Note: Root mean square values are denoted by the relevant symbols for all sinusoidal varying voltages, currents and sound pressures, unless otherwise stated.)

The total electrical power P_e may be expressed in terms of several parts:

$$P_e = P_e + P_{ml} + P_a = P_d + P_m \tag{2}$$

where

$$P_m = P_{ml} + P_a \qquad (3)$$

where P_a is the acoustic power output, P_d is the electrical power loss due to piezoceramic losses, P_{ml} is the internal mechanical loss power and P_m is the total mechanical power delivered by the transducer.

6.2 Electro-acoustical efficiency of the transducer η_{ea}

The ratio expressed as a percentage of the acoustic power P_a to the electrical input power P_e:

$$\eta_{ea} = P_a/P_e \times 100\% \qquad (4)$$

The value of η_{ea} may be expressed as:

$$\eta_{ea} = \eta_{em} \times \eta_{ma} \qquad (5)$$

where η_{em} is the electro-mechanical efficiency of the loaded transducer and η_{ma} is its mechano-acoustical efficiency.

6.3 Electro-mechanical efficiency η_{em}

The ratio expressed as a percentage of the total mechanical power P_m to the electrical power P_e:

$$\eta_{em} = P_m/P_e \times 100\% \qquad (6)$$

6.4 Mechano-acoustical efficiency η_{ma}

The ratio expressed as a percentage of acoustic output power P_a to the total mechanical power P_m:

$$\eta_{ma} = P_a/P_m \times 100\% = P_a/(P_a + P_{ml}) \times 100\% \qquad (7)$$

6.5 Vibrational displacement amplitude ξ

The amplitude of mechanical vibration or displacement at the active face of the ultrasonic transducer, or at the output end of a mechanical transformer attached to the transducer.

6.6 Frequency of Resonance f_{res}

The natural frequency of the electromechanical system corresponding to the maximum value of the electrical input power P_e or to the maximum of the vibrational displacement amplitude ξ (vibrational velocity amplitude $v = \xi \omega$).

The frequency f_{res} depends on the electric output impedance $Z_{g\ out}$ of the supply generator. When $Z_{g\ out}$ is very low in comparison with the electrical impedance Z of the transducer and the driving voltage is maintained constant with varying frequency (V_r = constant), f_{res} nearly coincides with the anti-resonant frequency f_a. When $Z_{g\ out}$ is very high in comparison with the electrical impedance of the transducer and the driving current is maintained constant with varying frequency (I_r = constant), f_{res} approximately coincides with the series resonant frequency f_r. In actual conditions the resonant frequency f_{res} is usually between f_r and f_a.

6.7 Resonant frequency f_r

The frequency of resonance in the case where the transducer is excited by a constant voltage power supply (the output impedance $Z_{g\ out}$ being very large compared to Z). It is approximately equal to the frequency corresponding to the maximum electrical impedance of the transducer or to the maximum vibrational velocity amplitude and maximum input power at a constant driving current.

6.8 Anti-resonant frequency f_a

The frequency of resonance in the case where the transducer is excited by a constant voltage power supply (the output impedance $Z_{g\ out}$ being very small compared to Z). It is approximately equal to the frequency corresponding to the minimum impedance of the transducer or to the maximum vibrational velocity amplitude and maximum input power at a constant driving voltage.

6.9 Bandwidth Δf

The frequency interval around the resonance in the frequency response curve of the transducer, limited at both sides of f_{res} by the frequencies corresponding either to magnitudes of P_e equal to 0.5 of its maximum value or to magnitudes of ξ equal to 0.707 of its maximum value.

6.10 Frequency response curve (at constant voltage)

The values of P_e or ξ are plotted against frequency with a constant value of V_T. The frequency range of the curve should be extended as far as necessary to properly describe the transducer under its loading conditions.

6.11 Frequency response curve (at constant current)

The values of P_e or ξ are plotted against frequency with a constant value of I_T. The frequency range of the curve should be extended as far as necessary to properly describe the transducer under its loading conditions.

6.12 Mechanical quality factor Q

This is a measure of the mechanical losses in a transducer. It is defined as:

$$Q = f_{res} / \Delta f \qquad (8)$$

6.13 Electrical impedance of the transducer, Z

The ratio of the a.c. driving voltage on its terminals to the corresponding a.c. current flowing to the transducer. It may be expressed in the form:

$$Z = |Z|\, e^{j\phi} \qquad (9)$$

where the magnitude of the transducer impedance measured in ohms is

$$|Z| = V_T / I_T \qquad (10)$$

and ϕ is the phase shift angle between the driving voltage and the current. Another form for the impedance is:

$$Z^2 = R^2 + X^2 \qquad \tan\phi = X/R \qquad (11)$$

where R is the real and X is the imaginary component of Z.

6.14 Electrical impedance at resonance Z_{res}

The value of the electrical impedance of the transducer at its frequency of resonance is Z_{res}.

6.15 Damped electrical impedance of the transducer Z_d

The electrical impedance of the transducer in the absence of mechanical vibrations is Z_d.

6.16 Mechanical stress σ

The mechanical stress generated in the material is σ.

6.17 Mechanical prestress σ_0

The permanent mechanical bias stress applied to the piezoceramic material is σ_0.

6.18 Modulus of Elasticity Y

Young's Modulus or the modulus of compliance (The ratio of stress-to-strain in the material).

6.19 Electromechanical coupling k

The electromechanical coupling k is a figure of merit that describes the efficiency of the material, or transducer, in converting electrical energy into mechanical stored energy.

7 Measuring conditions

7.1 Introduction

The measurement of transducer characteristics should be performed under conditions closely approximating to the conditions of operation and include temperature, drive level and load impedance. These can be summarized as:

(a) Maintain transducer at the temperature of the surrounding liquid or gas.
(b) Actively cool the transducer.
(c) Transducer is supported in a free-free configuration.

(d) Shroud the non-operative faces (sides and rear surfaces).
(e) Load the active faces.

Transducer characteristic measurements described in Section 6 will be made without an external load if the transducer impedance is greater than the external load impedance (see Clause 3.1). Measurements of transducer characteristics shall be performed with the operating load impedance. Transducers classified under Clauses 3.2 and 3.3 typically operate with a variable load. Therefore, the load used during test must be specified in detail.

7.2 Recording of operating parameters

During the measurement procedures, the operating parameters such as the a.c. driving voltage or the input power shall be in accordance with rated values corresponding to actual operating conditions. It is not recommended that extrapolation of low power values are used to define high power operation. The values of power level, drive voltage, and other parameters that may affect the measurement results shall be shown together with the measured results.

7.3 Acoustic liquid load

The liquid for measurements of transducers classified under Clause 3.2 shall be water (see Appendix A, Clause A2). The optimum liquid level above the radiating surface of the transducer should be specified by the manufacturer, or the level should be at least two wavelengths at the frequency of the transducer.

7.4 Preparation for measurement of immersed transducers

Previous to immersion, all transducer surfaces and parts, which will be immersed in water during measurements, shall be carefully cleaned so as to be free from contamination and grease, preferably by ultrasonic cleaning. If materials are subject to corrosion by water, e.g., iron alloys, the transducer should be immersed for a minimum time and carefully dried after test.

If no special requirements for positioning the transducer under working conditions are specified, the transducer shall be positioned during measurements in such a way that gas bubbles cannot accumulate on the active face, (see Appendix A, Clause A2).

7.5 Preparation of water

In order to reduce the release of gas bubbles during ultrasonic activity, the water should be degassed by an approved method, (see Appendix A, Clause A3). If this has involved heating, the water is then cooled to the working condition temperature.

7.6 General requirements for applied instrumentation

The frequency capability and dynamic range of the driving power generator and amplifier if used as well as all ancillary instrumentation should be adequate for the range of frequencies of the transducers under measurement. Frequency discrimination should be digital, allowing an accuracy of reading to at least 10 Hz within a frequency range of up to 100 kHz.

The output of the generator shall be adjustable over the range of power required for testing and the output should be stable under varying load conditions.

7.7 Digital data acquisition

Care must be taken when using digital data acquisition to ensure that errors are not introduced during the signal processing. Conventional practices for analog-to-digital conversion and digital-to-signal processing should be observed (see Appendix E).

8 Measuring procedures

8.1 Electrical input power

8.1.1 Wattmeter method

The wattmeter method is the primary method for measuring the electrical a.c. power of any type of ultrasonic transducer. In this method, the magnitude of P_e is determined directly as the reading on the scale of a wattmeter. The following requirements apply to the instrument: it shall permit measurements to be performed not only with sinusoidal driving voltage and current, but also with a time constant of less than 1 s. The measuring error should not be more than ± 5% under any kind of load, including low power factor loads (small values of $\cos\phi$).

8.1.2 Impedance method

The impedance method is a secondary method and it is used if a wattmeter having the required properties is not available and the operating conditions are sufficiently linear, i.e., the distortions of the sinusoidal waveform of the transducer voltage and current are negligible. The magnitude of P_e is calculated in this method according to one of the formulae:

$$P_e = V_T I_T \cos\phi = V^2_T / |Z| \cos\phi \qquad (12)$$

$$P_e = I^2_T R = V^2_T / (R^2 + X^2) R \qquad (13)$$

The components of the electrical impedance of the transducer Z, R, and X defined in Sub-clause 6.13 are measured by one of the well-known methods (see Clause 8.6).

V_T is the reading on the scale of an electronic voltmeter measuring the a.c. voltage on the transducer terminals and I_T is the reading on the scale of the high-frequency ampere meter measuring the a.c. current to the transducer. The magnitude of I_T may also be determined as V_R/R_S, where V_R is the voltage across a small non-reactive resistor of magnitude R_S connected in series with the transducer. The instruments shall satisfy the following requirements: uncertainties in measurement of V_T, I_T and V_R shall not be more than ± 1% and the magnitude of R_S shall be known with an uncertainty of less than ±1%.

8.1.3 Three-voltmeter method

The three-voltmeter method is a secondary method, used under the same conditions as the impedance method (see Sub-clause 8.1.2). The magnitude of P_e is calculated in this method according to the formula:

$$P_e = V^2_G - V^2_R - V^2_T / 2R_S \qquad (V_T \text{ or } V_T^2 \text{ ??}) \qquad (14)$$

where V_T and V_R are the a.c. voltages respectively across the transducer and across the resistor of magnitude R_S connected in series with the transducer, and V_G is their summed voltage. The basic circuit of the method is shown in Figure 1.

In measuring practice, a switching device is recommended in order to perform all the voltage measurements by means of one and the same instrument with an uncertainty of not more than ± 2%.

For greatest accuracy, the magnitude of the resistor should be approximately equal to the magnitude of the transducer impedance Z and known with an uncertainty of not more than ±1%.

Notes

1. The load impedance of the driving generator (amplifier) is now equal to $R_S + Z$. The output impedance of the generator should be matched to this new load impedance.

2. The power dissipated by the resistor R_S may be of the same order of magnitude as the power consumed by the transducer. The generator should be able to provide this additional power, while the resistor should have the proper power handling capacity.

3. In the measuring procedure, the interchange of Z and R_S by means of a switching device is necessary because of the earthing conditions of the voltage-measuring instrument. If the transducer also requires an earthed connection, this method is not applicable.

8.2 Acoustical output power and electro-acoustical efficiency

8.2.1 Calorimetric-wattmeter method

The calorimetric-wattmeter method is the primary method for measurement of the electro-acoustical efficiency of transducers with a liquid load. The electro-acoustical efficiency η_{ea} is calculated directly as the ratio of acoustical power P_a radiated into the liquid to the electrical power P_e (see Sub-clause 6.2).

The radiated acoustical power is measured by the calorimetric method, and the electrical input power by means of a wattmeter (see Sub-clause 8.1.1). When the linearity conditions are fulfilled, the magnitude of P_e may also be measured by the impedance method, or by the three voltmeter method (see Sub-clauses 8.1.2, 8.1.3).

In the calorimetric method of measuring acoustical power, water is used for the liquid load, meeting the requirements of Clauses 7.3 and 7.5. The general measuring procedure is as follows: the transducer is switched on and the temperature difference T_2-T_1 arising in the tank during its operation time Δt is measured (see Figure 2). The magnitude of P_a is calculated according to the formula:

$$P_a = cm\,(T_2 - T_1)/\,\Delta t \tag{15}$$

where c is the specific heat of water and m is the mass of the water.

A number of thermocouples (about ten), usually copper-constantan, and a potentiometer are used for temperature measurements. If the temperature difference to be measured exceeds 2 ^{o}C, a thermometer with scale divisions of 0.1 ^{o}C or smaller may be used instead of thermocouples.

The following conditions shall be fulfilled to ensure reasonable accuracy of the method (see Appendix B):

a) The time interval t shall not exceed 30 s (its optimum value being about 10 s);

b) The temperature T_1 at the moment of switching on the transducer should not differ from the ambient temperature by more than 3 ^oC to 5 ^oC;

c) The method is not applicable in cases of very low P_a values, when the temperature rise in the water tank during 30 s of transducer operation is less than 1 ^oC.

Other precautions should not be taken to prelude the possibility that the heat exchange between the liquid in the tank and the tank walls or the surroundings may effect the results (see Appendix B).

The uncertainty in temperature measurements shall be not more than 0.2 ^oC and the uncertainty in time measurements shall be not more than 0.5 s. With such accuracy of measurement and all the above-mentioned conditions fulfilled, the uncertainty in the calorimetric method of evaluation of acoustical power will not be more than ± 10%, and that of the electro-acoustical efficiency not more than ±15%.

8.2.2 Power flow method

The power flow method is the primary method for measurement of the electro-acoustical efficiency of transducers propagating into a solid load (per Clause 3.3).

The electro-acoustical efficiency is determined by a method similar to the calorimetric wattmeter (see Sub-clause 8.2.1), the only difference being in the measurement of the acoustical output power P_a. The value of P_a is measured by introducing a mechanical transmission line, for example, a cylindrical metal rod with a length equal to a multiple of half-wavelengths, between the transducer and the load and by employing the method of power measurement described below (see Appendix F: Bibliography [2] and [11]).

The measurement arrangement is outlined in Figure 3. Calibrated vibrometers are used whose output voltage is proportional to the axial vibrational displacement in the transmission line. The vibrometers may be positioned without regard to nodes and antinodes. Filters F_1 and F_2 are required to have identical cut-off frequencies.

For measurement in the non-linear range, a total suppression of second harmonic power flow signals is achieved by choosing f_{res} /2 as the cut-off frequency for the filters and $\lambda/6$

as the distance d between the vibrometers, where λ is the wavelength in the transmission line. Then the magnitude of P_a is calculated according to the formula:

$$P_a = 5 / \sqrt{3} \text{ x } (Z_L S_L V_O) / Y_1 Y_2 \text{ x } V_m \qquad (16)$$

where Z_L is the specific acoustic impedance of the transmission line, S_L is its cross-sectional area. Y_1 and Y_2 are the sensitivities of the vibrometers, determined as their output voltage divided by the vibrational velocity, V_O is the reference voltage of the electronic multiplier, determined as the product of its input voltage divided by its output voltage

$$V_o = V_1 \text{ x } V_2 / V_m \qquad (17)$$

The output voltage V_m of the low pass filter F_3 is used for the calculation of the net acoustic power P_a. In order to obtain an extremely quick response of V_m to power flow fluctuations, it is recommended to implement F_3 as a Bessel-type low-pass filter of the fourth order with a cut-off frequency of $f_{res}/ 2$.

8.2.3 Wattmeter method

The wattmeter method is a secondary method for measurement of the acoustical output power and electro-acoustical efficiency of transducers with liquid load, but a primary method for that of transducers with gas and solid loads. In this method the magnitude of P_a is calculated according to the following formula: The electro-acoustical efficiency is determined by a method similar to that described in Sub-clause 8.2.1 but with a different measurement of acoustical power P_a. In this method, the magnitude of P_a is calculated according to the formula:

$$P_a = (P_{e\,fo} - P'_{e\,fo}) = (P_d \text{ x } P'_d) \qquad (18)$$

where $P_{e\,fo}$ and $P'_{e\,fo}$ are the values of electrical input power in the loaded and unloaded conditions respectively, measured at the frequency f_o (loaded) and unloaded of the resonance at the same vibration velocity, equal to the rated value (see Fig. 4A).

The measurements of electrical power are carried out by a high frequency wattmeter.

Measurement of the vibration amplitude is performed by means of a non-contact vibrometer of any type (see Sub-clause 8.3.2) mounted at the rear end of the transducer.

[NOTE: For reference purposes, the 1997 wording of the above section is included:
The wattmeter method is a secondary method for measurement of the electro-acoustical efficiency of transducers. The electro-acoustical efficiency is determined by a method similar to that

described in Sub-clause 8.2.1 but with a different measurement of acoustical power P_a. In this method, the magnitude of P_a is calculated according to the formula:

$$P_a = (P_{e\,res} - P'_{e\,res}) - (P_{el} - P'_{el}) \qquad (18)$$

where $P_{e\,res}$ and $P'_{e\,res}$ are the values of electrical input power in the loaded and unloaded conditions respectively, measured at the frequency of resonance at the same vibration velocity, equal to the rated value and P_{el} and P'_{el} are the values of electrical loss power "on load" and at "no load." The measurement of $P_{e\,res}$ and $P'_{e\,res}$ are carried out by one of the usual methods (see Clause 8.1). Measurement of the vibration amplitude is performed by means of a non-contact vibrometer of any type (see Sub-clause 8.3.2) mounted at the rear end of the transducer.]

If V_{TO} and V'_{TO} are the transducer voltages at resonance corresponding to the input powers $P_{e\,res}$ and $P'_{e\,res}$ (points A and A_1 in Figure 4) then the values of P_{el} and P'_{el} are obtained by plotting P_e versus f while the transducer is driven by the voltage

$$f_{res} / f \times V_{TO} \quad \text{or} \quad f'_{res} / f \times V'_{TO} \qquad (19)$$

respectively.

The interpolation lines for P_e from out-of-resonance regions, the asymptotes of the curves, are drawn; the ordinates of these lines, corresponding to the frequencies of resonance, denote the value of P_{el} and P'_{el} (points C and C_1 on Figure 4).

This method is restricted by the requirements that the transducer voltage and its surface displacement shall be of sinusoidal form. With the uncertainty of electrical power measurements not more than ±5%, the uncertainty of the acoustical power evaluation shall not be more than ±10%, and that of the electro-acoustical efficiency not more than ±15%.

8.2.4 Impedance diagram method

The impedance diagram method is a secondary method for measurement of the electro-acoustical efficiency. This method may be applied only in strictly linear cases and when liquid loaded only in the absence of standing waves in the tank.

If parasitic resonances disturb the impedance plot near the main resonance, the method is not applicable.

In this method, the values of the complex electrical impedance of the transducer are plotted on the R-X plane for different frequencies in the range $f_{res} \pm f$ depending on the Q-factor of the transducer. Measurements of R and X are carried out by one of the known methods (see Clause 8.6) with an uncertainty of not more than ± 2%.

Electronic devices for automatically plotting of the impedance diagram on the oscilloscope screen or the recorder may also be used, provided their accuracy is sufficient.

The impedance diagram forms a circle near the resonance frequency (see Figure 5). The electro-acoustical efficiency η_{ea} is calculated as the product of η_{em} and η_{ma} (see Sub-clause 6.2). Magnitudes of η_{em} and η_{ma} are determined according to the formulae:

$$\eta_{em} = d / (d + R_d) \qquad (20)$$

$$\eta_{ma} = (D - d) / D \qquad (21)$$

where D is the diameter of the impedance circle, corresponding to “no load” conditions, d is that corresponding to “on load” conditions; R_d is the real component of the blocked transducer impedance, i.e., the value of the real part of the impedance at the point where the circle is next to the out-of-resonance part of the curve.

The accuracy of the method is about ± 10%; the averaging of dispersion of experimental points being important when no automatic plotting is available.

8.3 Vibrational displacement amplitude

8.3.1 Optical microscope method

The optical microscope method is the primary method for measurement of the vibrational displacement amplitude of transducers and for calibration of vibrometers of different types. In this method, a microscope is focused on a point on the special illuminated side surface of the transducer (usually on its mechanical transformer output end or on that of the attached tool in the absence of the load). When the transducer is set into vibration along its axis, this point becomes a line, perpendicular to the radiating face. The line length, equal to twice the displacement amplitude 2ξ is measured by means of the calibrated eyepiece micrometer. If transverse vibrations occur simultaneously, the line acquires an inclination to the transducer axis or, in the case of a phase shift, the line degenerates into an ellipse. The axial direction component of the inclined line or the dimensions of the observed figure in the axial direction should then be measured. Microscope magnification shall be about 100 to 800 times. The method is restricted to a minimum displacement amplitude of 2 μm.

8.3.2 Vibrometer methods

The methods, using vibrometers of different types for the measurement of transducer vibrational displacement amplitude, are secondary methods, used for transducers in an unloaded condition. They are also applicable for measurements of the displacement amplitude at the rear side of transducers in the loaded condition. Non-contacting high-frequency vibrometers of different types should be used in this method (see Appendix D). The scale of the instrument should be graduated directly in micrometers, its frequency range being 8 kHz to 100 kHz, and the dynamical range 0.5μm to 100μm. The measurement error should not be more than ± 10%.

8.4 Frequency of resonance of the transducer

8.4.1 Maximum power method

The maximum power method is the primary method for measurement of the frequency of resonance for transducers. The frequency of resonance f_{res} of transducers under load is determined from the frequency corresponding to the maximum input power P_e . When obtaining the frequency characteristic, the transducer is supplied from the same generator as in normal working conditions. As an exception it is possible to determine f_{res} from the P_e frequency characteristics taken at lower values of V_T and P_e than the rated ones, since the non-linearity of the transducer and load properties do not much affect the frequencies of resonance.

The magnitude of the input power is measured by one of the known methods (see Clause 8.1). The frequency, corresponding to maximum P_e is measured by means of an electronic frequency meter.

This method may also be used for transducers in the unloaded condition.

The value of f_{res} should be determined with an error of not more than ± 5% for liquid loaded transducers and with an error of not more than ± 0.5% for unloaded transducers.

If the magnitude of V_T is kept constant during measurement of P_e versus frequency, the value of the frequency of resonance obtained by this method is approximately equal to f_a. In the case of constant magnitude of I_T the frequency of resonance is approximately equal to f_r.

8.4.2 Maximum amplitude method

The maximum amplitude method is a secondary method for measurement of the frequency of resonance of transducers.

The frequency of resonance f_{res} of the transducers is determined as corresponding to the maximum value of the displacement amplitude ξ. When obtaining the frequency characteristic the transducer is supplied from the same generator as in normal working conditions. If the magnitude of V_T is kept constant, this maximum occurs at the frequency approximately equal to f_a; with constant I_T the maximum occurs at the frequency approximately equal to f_r. The amplitude measurements are carried out by means of a non-contact vibrometer (see Sub-clause 8.3.2); for frequency measurements an electronic frequency meter is used, the frequencies being determined with an uncertainty of not more than ±0.5%.

8.4.3 Impedance characteristic method

The impedance characteristic method is a secondary method for measurement of the frequency of resonance for transducers, applicable only in the linear range. In this method, frequencies f_r and f_a are determined, and f_{res} corresponding to real working conditions is located between them (see Sub-clause 6.6). As an exception to the general rule, measurements of frequencies f_r and f_a are performed for transducers in the unloaded condition and at an excitation level much lower than the rated one.

The impedance frequency characteristics shall be obtained in two forms:

a) The voltage on the electrical terminals of the transducer V_T is plotted versus frequency, with the transducer current I_T maintained constant. The frequency, at which V_T is maximum, is approximately f_r (see Figure 6a).

b) The transducer current I_T is plotted versus frequency, with the transducer voltage V_T maintained constant. The frequency, corresponding to maximum I_T is approximately f_a (see Figure 6b).

Constant current conditions may be realized in an experimental device by connecting in series with the transducer a resistor, the magnitude of which is about 100 times greater than the transducer impedance. Constant voltage conditions are realized by feeding the transducer from a very low impedance source.

Measurements of V_T should be performed with an uncertainty of not more than ±1%, while the uncertainty in measurement of I_T may not exceed ±1.5%.

The frequency is determined by means of an electronic frequency meter. For cases where the complex impedance of the transducer in the frequency range near the resonance is known (i.e., where the impedance diagram of the transducer is available - see Sub-clause

8.2.4), frequencies f_r and f_a may be determined as corresponding to certain points on this diagram which are found by simple geometrical construction, as shown in Figure 4.

8.5 Bandwidth and mechanical quality factor

8.5.1 Input power frequency characteristic method

The input power frequency characteristic method is the primary method for measurements of the bandwidth and the mechanical quality factor of transducers. In this method the frequency response curve of the transducer in the form of the dependence of its input power P_e on the frequency f is plotted and the bandwidth Δf is determined as a frequency interval limited by the frequencies located at each side of the frequency of resonance (see Sub-clause 8.4.1) which correspond to the magnitudes of P_e equal to half of its maximum value. The mechanical quality factor Q is calculated as the ratio of f_{res} to Δf (see Sub-clause 6.9). The measurements of P_e are performed by one of the above-mentioned methods (see Clause 8.1) and the frequency is determined by means of an electronic frequency meter.

8.5.2 Amplitude frequency characteristic method

The amplitude frequency characteristic method is a secondary method for measurements of the bandwidth and the mechanical quality factor of transducers. The frequency response curve of the transducer in the form of the dependence of the displacement amplitude ξ on the frequency is plotted and the bandwidth Δf is determined as a frequency interval limited by the frequencies located at each side of the frequency of resonance f_{res} (see Sub-clause 8.4.2) which correspond to the magnitudes of ξ equal to 0.7 of its maximum value. The mechanical quality factor Q is calculated as the ratio of f_{res} to f (see Sub-clause 6.9). The measurements of ξ are performed by one of the above-mentioned methods (see Clause 8.3) and the frequency is determined by means of an electronic frequency meter.

8.6 Electrical impedance of the transducer at resonance

8.6.1 Voltmeter and wattmeter method

The voltmeter and wattmeter method is the primary method for measurement of the electrical impedance of transducers. It may be applied in cases where the transducer voltage is of sinusoidal waveform. In this method, the magnitude of the transducer impedance $|Z|$ is determined as the ratio of transducer voltage V_T to transducer current impedance I_T (see Sub-clause 6.13). The magnitude of I_T may be determined as V_R/R_S, where V_R is the voltage across a small non-reactive resistor of magnitude R_S connected in series with a transducer.

The phase angle ϕ is determined according to the formula:

$$\cos \phi = P_e / V_T I_T \quad (22)$$

with P_e measured by one of the above-mentioned methods (see Clause 8.1).

When performing measurements the excitation generator should be tuned on the frequency of resonance of the transducer and the frequency measured by an electronic frequency meter.

The uncertainty of voltage measurements should not be more than ±2% and that of power measurements not more than ±5%. Therefore the uncertainty in $|Z|$ measurements should be not more than ±5% and in $\cos \phi$ not more than ±10%.

8.6.2 Bridge method

The bridge method is a secondary method for measurements of the electrical impedance of transducers in the strictly linear range.

The real and imaginary components R and X of the transducer impedance are measured by means of an impedance or admittance bridge of any kind, provided its frequency range includes the frequency of resonance of the transducer. The uncertainty in bridge measurements should be no more than ± 2%.

8.6.3 Voltmeter and phasemeter method

The voltmeter and phasemeter method is a secondary method for measurement of the electrical impedance of transducers in the strictly linear range. The measuring procedure in this method is nearly the same as for the voltmeter-wattmeter method (see Sub-clause 8.6.1), the difference being in the measurement of the phase angle ϕ. The latter is determined by means of an electronic phasemeter which has a frequency range including the frequency of resonance of the transducer and an uncertainty in phase angle measurements of not more than ± 2%.

8.6.4 Three voltmeter method

The three voltmeter method is a secondary method for measurement of the electrical impedance of transducers in the strictly linear range. The measuring arrangement and procedure is as for the three voltmeter method (see Sub-clause 8.1.3); the values of $|Z|$ and cos ϕ are calculated according to the formulae:

$$|Z| = (V_T / V_R) \times R_S \tag{23}$$

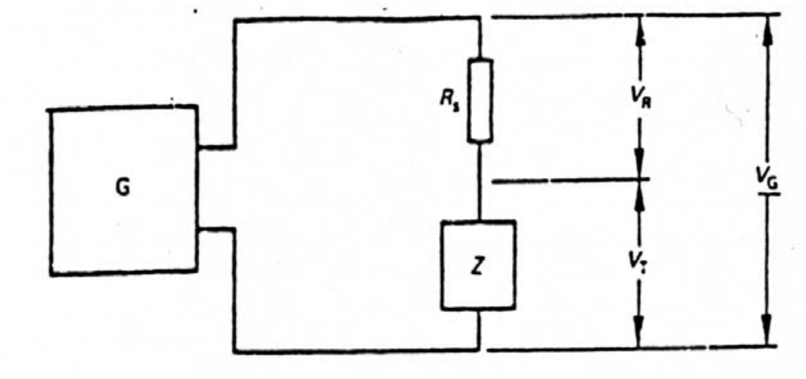
$$\cos \phi = (V^2_G - V^2_R - V^2_T) / 2V_R V_T \tag{24}$$

8.7 Blocked (damped) electrical impedance of the transducer

In order to obtain the value of the blocked electrical impedance of the transducer corresponding to working conditions, the components of the complex electrical impedance are measured outside the resonance region at a number of frequencies below and above f_{res}, the ratio of V_T / f being maintained equal to the rated one at the frequency of resonance. Any method of measurement of transducer impedance may be used (see Clause 8.6). A line is drawn through the experimental points, plotted on the $|Z| - f$ plane, which is the frequency characteristic of the blocked transducer impedance, and its ordinate, corresponding to f_{res}, denotes the required magnitude of the blocked impedance of the transducer under working conditions.

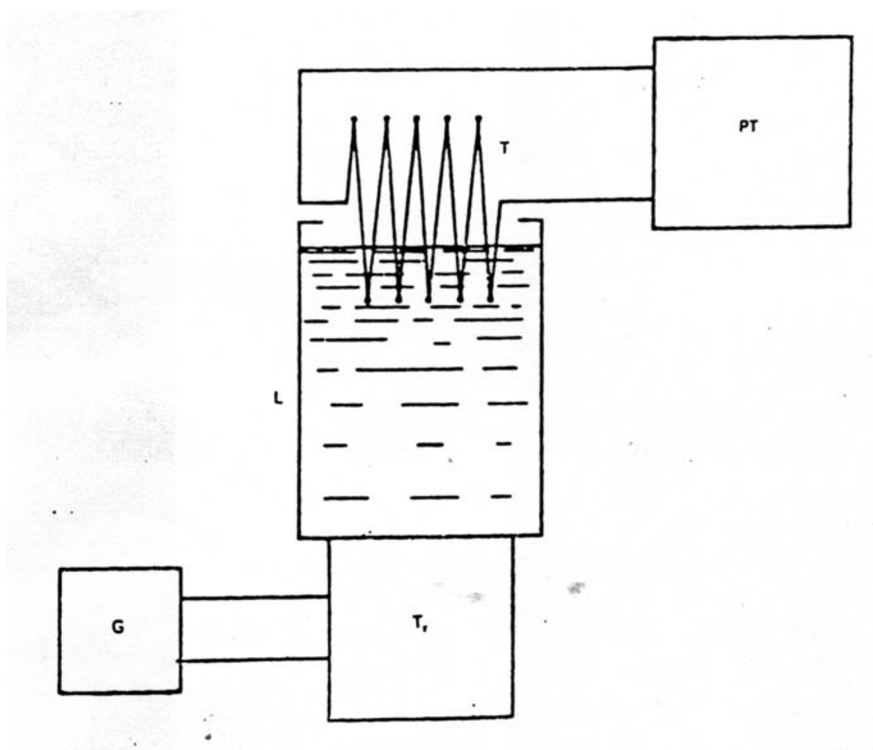
The same procedure is performed with the cosϕ value, plotting the frequency characteristic of cosϕ of the blocked transducer and finding by interpolation its value at f_{res}.

9 Figures



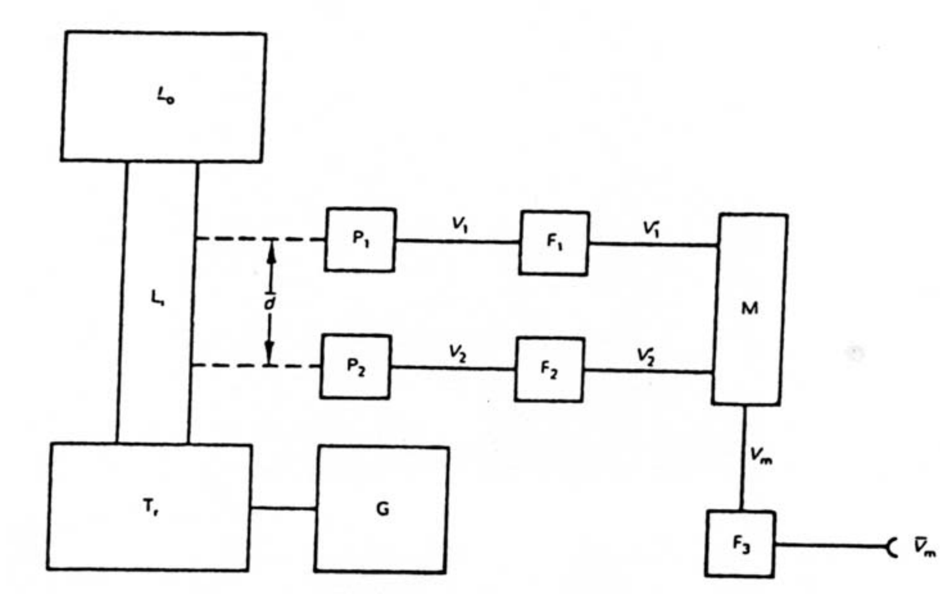
Z = transducer electrical impedance
R_S = series resistor
G = excitation generator

Fig. 1 Basic circuit of the three-voltmeter method



Tr = transducer
G = excitation generator
L = water tank (calorimeter)
T = thermocouples
PT = potentiometer

Fig. 2 Measuring arrangements for the calorimetric method



G = excitation generator
T_r = transducer
L_1 = transmission line
L_o = load
P_1, P_2 = vibrometers
F_1 = first order low-pass filter
F_2 = first order high-pass filter

M = electronic multiplier
F_3 = low-pass filter
d = distance between vibrometers
V_1, V_2 = output voltages of vibrometers
V_1 = output voltage of the low-pass filter F_1
V_2 = output voltage of the high-pass filter F_2
V_m = output voltage of the low-pass filter F_3

Fig. 3 Measuring arrangement of the power flow method.

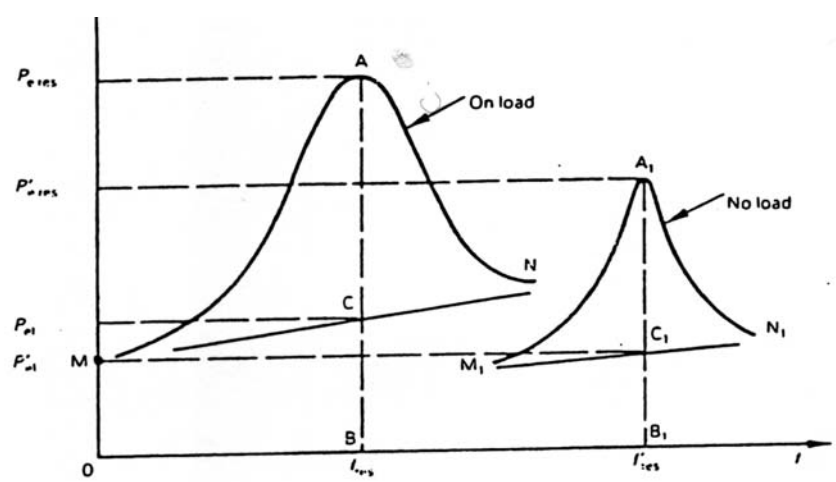


Fig. 4 Frequency characteristics of electrical input power of the transducer. M - N and M_1 - N_1 are frequency characteristics of the electrical loss power in the loaded and unloaded conditions respectively.

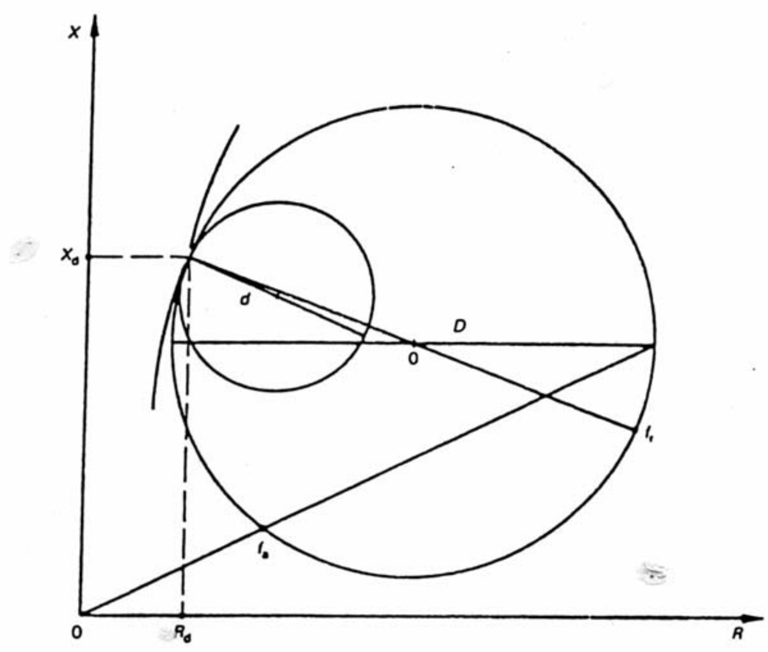


Fig. 5 Impedance diagrams of loaded (diameter D) and unloaded (diameter d) transducer

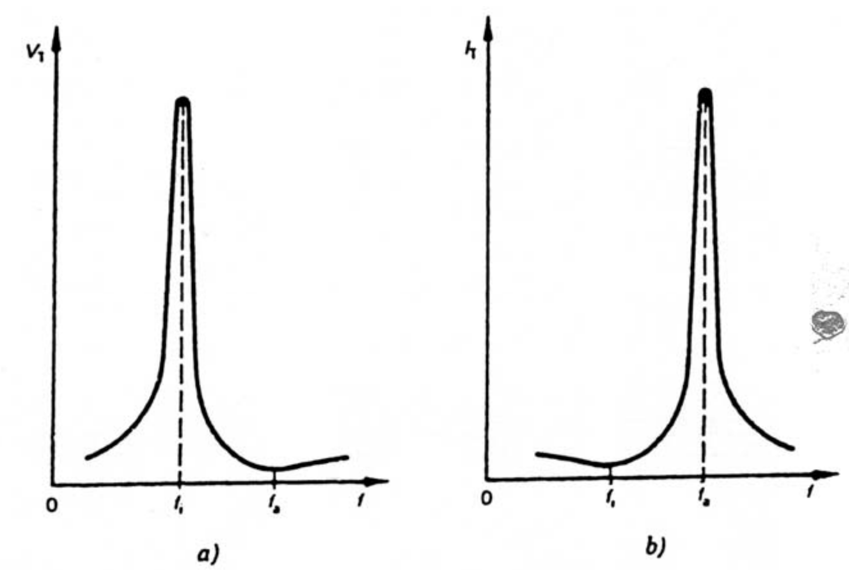


Fig. 6 (a) Frequency characteristics of transducer voltage with the transducer suppled at constant current.

(b) Frequency characteristics of transducer current with the transducer supplied at constant voltage.

10 Appendixes

Appendix A: MEASURING CONDITIONS

A1 Influence of non-linearity

Input power and driving voltage levels in measurement shall be the same is in actual operation to limit non-linearity of the magnetic and mechanical properties of the transducer and that of the acoustic properties of the loading liquid due to cavitation.

The primary manifestation of transducer non-linearity is the dependence of dielectric losses on the driving voltage and of mechanical losses on the vibrational displacement amplitude.

There is also a driving voltage dependence of electromechanical transformation coefficients.

A2 Influence of air bubbles and contaminants.

When measuring transducers of the immersion type radiating into water or other liquids, the medium should be degassed, although in most operating conditions liquids are usually naturally saturated with air or other gases. However, the measurements with a saturated liquid load are generally unstable due to the adhesion of bubbles and the possibility of cavitation at relatively low power levels.

The reproducibility of measurements is more important than the exact simulation of operating conditions. Cleaning the active transducer face before measurements is necessary as the surface contamination may stick and retain small bubbles. These will have a considerable influence on the results.

A3 Methods for degassing water and some other liquids.

It is recommended to use distilled and filtered water to avoid suspended solids. A number of methods are available for degassing water and the following are representative. The efficacy of the procedures may be checked by determination of the dissolved oxygen content in samples of degassed water using dissolved oxygen test kits.

A3.1 Boiling

(a) Water maintained at boiling temperature for 15 minutes
(b) Cooled to 54^0C.
(c) Bottle filled to brim with the boiled water and closed with a rubber stopper having a glass tube and rubber hose attached. The hose should be completely filled with water and then clamped.

(d) Cooled and stored until needed with a partial vacuum maintained in the hose.

A3.2 Boiling at reduced pressure.

Water boiled under reduced pressure (less than 10^4 Pa) in 20 litre glass jars using electric immersion heaters, then allowed tocool to 39^0C overnight. The same temperature and reduced pressure are maintained until the water is used (one day to one week later).

A3.3 Reduced pressure spray

Water is passed into a partially evacuated flask (pressure less than 10^4Pa) in the form of a fine spray. Degassing is effected by the agitation of the inflowing water combined with the large surface area of the droplets.

Appendix B: BASIS OF THE CALORIMETRIC METHOD OF MEASURING THE ACOUSTIC POWER AND ITS LIMITATIONS

The calorimetric method of measuring acoustical power is based on the effect of sound absorption in liquids and their heating due to the absorbed energy. It is well suited for measuring the acoustical power in the non-linear range, i.e. at high-power levels.

It may also be used at low levels, provided that the temperature rise due to ultrasound absorption in the liquid is not too small. At high energy levels the liquid may partly vaporize or atomize. The energy used for this does not contribute to the heating of the liquid. Therefore the energy level should not be too high. Some factors may considerably reduce the accuracy of the method, notably the direct heat conduction from the transducer to the liquid load, heat exchange between the liquid and the surroundings and the occurrence of standing waves.

In order to eliminate or to diminish the influence of the first factor the operating time of the transducer shall not exceed 20 s to 30 s. The slowness of the instrument for the temperature measurement shall however be taken into consideration. When thermometers with small scale divisions are used, the temperature indication probably reaches its maximum value some time after the energy supply has been switched off, and therefore this indication shall be awaited. Because of this, the duration of the measurement will be longer than 20 s to 30 s. Therefore, thermometers with small time constants shall be used and the operating time of the transducer shall be short.

The influence of the second factor (the heat exchange between the liquid and the surroundings) is reduced by making the initial temperature in the measuring tank nearly equal to the temperature of the surrounding media. Heat exchange with the surroundings may also be nearly completely excluded by using a standard calorimeter as a liquid tank.

Some modifications of the calorimetric method are used in order to eliminate the possibility that the heat absorption by the tank walls may affect the measurement results. These are compensation methods, using an equivalent heater in the form of an electrical wire heater with known consumed electrical power or in the form of a lump of meat with known mass, specific heat and high initial temperature. Comparing the heat of water in the measuring tank induced by the equivalent heater and by the ultrasound produced by the transducer, the acoustical power produced by the transducer can easily be calculated.

The use of calorimeters may introduce standing waves in the liquid bath, as a result of which the acoustic load of the transducer may change greatly. This can be verified by measuring the electrical impedance of the transducer and by changing its position in the bath.

Appendix C: BASIS OF THE WATTMETER METHOD AND OF THE IMPEDANCE DIAGRAM METHOD OF MEASUREMENT OF TRANSDUCER EFFICIENCY

The principle of measurement of the electromechanical efficiency in the wattmeter method is the separation at the frequency of resonance of the mechanical loss power and electrical loss power of a transducer by the interpolation of the magnitude of electrical loss power far away from resonance to the frequency of resonance, assuming that away from resonance no mechanical losses exist. The mechanoacoustical efficiency is determined by the comparison of mechanical losses of the transducer in the loaded and unloaded conditions.

In general, this method is suitable for transducers operating within the linear range. But provided that the requirements mentioned in Clause A1 of Appendix A are fulfilled, it may be used beyond the strictly linear range.

The impedance diagram method is also based on the frequency characteristics of the transducer in loaded and unloaded conditions and it is applicable only in linear range.

The value of η_{ea} obtained with the impedance diagram method corresponds to resonance under constant current conditions, i.e. to the frequency of resonance approximately equal to f_r, whereas η_{ea} obtained by the wattmeter is the efficiency corresponding to constant voltage conditions, that is to the frequency, approximately equal to f_a. However, for properly loaded transducers the difference in the magnitudes of η_{ea} at f_r and at f_a is negligible.

Appendix D: VIBROMETERS FOR NON-CONTACT MEASUREMENTS OF DISPLACEMENT AMPLITUDE

Devices for non-contact measurements of the vibration amplitude of a solid surface may be used on various principles.

In capacitive type vibrometers the probe is a small plane electrode, placed in front of the surface. It forms with the earthed surface a capacitor, in which the distance between the two plates varies periodically according to the vibrations. The effect of vibrations may be indicated exactly as in the condenser microphone, with d.c. voltage connected to the plates or the capacitor may serve as a part of a tuned circuit of an oscillator so that its capacitance variation gives rise to frequency modulation with a modulation index proportional to the vibration amplitude within certain limits.

In inductive type vibrometers the probe is a small coil, placed in front of the vibrating surface with its axis normal to the surface. The vibration effect may be indicated by the electromotive force, arising in the coil due to eddy-currents or the coil may be fed with high-frequency current and vibrations will cause modulation of this current. The coil may also serve as a part of a tuned circuit of an oscillator and the impedance variations due to vibrations will give rise to frequency modulation.

In the “Fotonic-sensor” type vibrometers the effect of vibrations is sensed by modulation of the amount of the reflected light. The light-transmitting and receiving elements are the butt-ends of glass fibres. Fiber-optic techniques are used in these devices.

Capacitor type and inductive type vibrometers may be used for measurements of electrically conductive materials; the optical-type vibrometers may be used for both conductive and non-conductive materials.

(Additional vibrometer types, including the laser type, should be considered for inclusion.)

Appendix E: DIGITAL SIGNAL PROCESSING

Conventional digital signal processing techniques can be used to obtain both time and frequency domain measurements of current, voltage, input electric power, electrical impedance and mechanical output.

The required quantities can be calculated in real time or during processing subsequent to the recording of signals. It is important to understand the operation of processing the signals in digital terms and several issues must be considered. These are:

1. Window functions

2. Sampling rate/frequency bandwidth
3. AC or DC coupling
4. Numerical integration
5. Aliasing uncertainties
6. Bias uncertainties
7. Resolution (digitization) uncertainties
8. Filter leakage
9. Averaging

Outline of Process.

Analog to Digital Conversion (ADC) of a signal allows automated storage, signal processing, and time and frequency domain analysis. The time domain signal is digitally sampled at a constant rate for a set length of time (record length) as defined by a sampling and window function respectively. The frequency domain representation of the signal is then accomplished through the use of fast Fourier transforms (FFT), which calculate the complex Fourier series components.

In order to calculate FFT's it is necessary to assume that the signal is periodic and only frequency components which are multiples of the fundamental frequency (one over the record length) are present in the signal. This process of sampling, windowing, and the assumptions of the FFT calculations lead to several problems. Undersampling leads to erroneous signal content. Therefore analog anti-aliasing filters are required; however, care must be taken because they can alter the signal.

The digitization of an analog signal leads to resolution uncertainties. ADC boards have attenuation settings that must be optimized to the maximum of the analog input signal to ensure good signal resolution. The periodicity assumption is not always valid for real signals, resulting in further contamination of the signal, known as leakage. A large variety of window functions can be used to minimize this effect. These window functions act as digital filters with their own unique characteristics that can contaminate the digital signal. In addition, multiple channel ADC which relies on multiplexing can produce time and phase shifts. These uncertainties and others resulting from the ADC and digital signal processing can be avoided or minimized with proper attention.

Appendix F: BIBLIOGRAPHY

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The below references have the numbers of the current magnetostrictive draft, with the nonapplicable references removed.

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