IEC TS 63001

Edition 1.0 2019-01

TECHNICAL SPECIFICATION

colour inside

Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

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IEC TS 63001:2019-01(en)

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 17.140.01; 17.140.50

ISBN 978-2-8322-6410-2

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MEASUREMENT OF CAVITATION NOISE IN ULTRASONIC BATHS AND ULTRASONIC REACTORS

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Technical Specification IEC 63001 has been prepared by IEC technical committee 87: Ultrasonics.

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The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
87/681/DTS	87/693A/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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INTRODUCTION

Ultrasonically induced **cavitation** is used frequently for immersion cleaning in liquids. There are two general classes of ultrasonically induced cavitation. **Transient cavitation** is the rapid collapse of bubbles. **Stable cavitation** refers to persistent pulsation of bubbles as a result of stimulation by an ultrasonic field. Both **transient cavitation** and **stable cavitation** may create significant localized streaming effects that contribute to cleaning. **Transient cavitation** additionally causes a localized shock wave that may contribute to cleaning and/or damage of parts. Both types of cavitation create acoustic signals which may be detected and measured with a **hydrophone**. This document provides techniques to measure and evaluate the degree of cavitation in support of validation efforts for ultrasonic cleaning tanks and cleaning equipment, as used, for example, for the purposes of industrial process control or for hospital sterilization.

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MEASUREMENT OF CAVITATION NOISE IN ULTRASONIC BATHS AND ULTRASONIC REACTORS

1 Scope

This document, which is a Technical Specification, provides a technique of measurement and evaluation of ultrasound in liquids for use in cleaning devices and equipment. It specifies

- the cavitation measurement at 2,25f_0 in the frequency range 20 kHz to 150 kHz, and
- the cavitation measurement by extraction of broadband spectral components in the frequency range 10 kHz to 5 MHz.

This document covers the measurement and evaluation of the cavitation, but not its secondary effects (cleaning results, sonochemical effects, etc.).

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
averaging time for cavitation measurement
t_{av}
length of time over which a signal is averaged to produce a measurement of cavitation

Note 1 to entry: Averaging time for cavitation is expressed in seconds (s).

3.2
cavitation
formation of vapour cavities in a liquid

3.2.1
transient cavitation
inertial cavitation
sudden collapse of a bubble in a liquid in response to an externally applied acoustic field, such that an acoustic shock wave is created

3.2.2
stable cavitation
oscillation in size or shape of a bubble in a liquid in response to an externally applied acoustic field that is sustained over multiple cycles of the driving frequency

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3.3
end of cable loaded sensitivity
$M_L(f)$
<of a **hydrophone** or **hydrophone assembly**> modulus quotient of the Fourier transformed output **voltage** $U(f)$ at the end of any integral cable or output connector of a **hydrophone** or **hydrophone-assembly**, when connected to a specific electric load impedance, to the Fourier transformed acoustic pressure $P(f)$ in the undisturbed free field of a plane wave in the position of the reference centre of the **hydrophone** if the **hydrophone** were removed, at a specified frequency

Note 1 to entry: The Fourier transform is in general a complex-valued quantity but for this document only the modulus is considered, and is expressed in volt per pascal, V/Pa,

Note 2 to entry: The term 'response' is sometimes used instead of 'sensitivity'.

3.4
end of cable loaded sensitivity level
$M_{L.dB}$
twenty times the logarithm to the base 10 of the ratio of the modulus of the **end of cable loaded sensitivity** $M_L(f)$ to a reference sensitivity of M_{ref}.

Note 1 to entry: $M_{L,dB} = 20 \log_{10} \frac{|M_L|}{M_{ref}}$ dB .

Note 2 to entry: The value of reference sensitivity M_{ref} is 1 V/Pa.

3.5
hydrophone
transducer that produces electric signals in response to waterborne acoustic signals

[SOURCE: IEC 60050-801:1994, 801-32-26] [1]

3.6
hydrophone assembly
combination of **hydrophone** and **hydrophone pre-amplifier**

[SOURCE: IEC 62127-3: 2007, 3.10] [2]

3.7
number of averages
N_{av}
number of waveforms captured and averaged in a **cavitation** measurement

3.8
operating volume
part of the liquid volume where cavitation effects are intended

3.9
operating frequency
f_0
driving frequency of ultrasound generator

Note 1 to entry: Operating frequency is expressed in hertz (Hz).

3.10
relative cavitation measurements
measurements made for purposes of comparison between two different cleaning environments or different locations within a cleaning environment, such that the **end-of-cable loaded sensitivity** of the **hydrophone** may be assumed to be identical in both cases

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Note 1 to entry: Care should be taken to ensure that changes in hydrophone sensitivity do not affect the measurement.

3.11
sampling frequency
f_s
number of points per second captured by a digital waveform recorder

Note 1 to entry: Sampling frequency is expressed in hertz (Hz).

3.12
size of the capture buffer
N_{cap}
total number of points captured at a time by a digital waveform recorder

3.13
capture time
t_{cap}
length of time to capture N_{cap} points at a sampling frequency of f_s

Note 1 to entry: Capture time is expressed in seconds (s).

3.14
cavitation noise level
L_{CN}
level calculated from the cavitation noise at a frequency of 2,25 f_0

Note 1 to entry: Cavitation noise is expressed in decibels (dB).

3.15
reference sound pressure
P_{ref}
sound pressure, conventionally chosen, equal to 20 μPa for gases and to 1 μPa for liquids and solids

Note 1 to entry: Reference sound pressure is expressed in pascals (Pa).

[SOURCE: IEC 60050-801:1994, 801-21-22] [1]

3.16
averaged power spectrum
$\overline{P^2}(f)$
power spectrum of the **instantaneous acoustic pressure** averaged over N_{av} measurements

Note 1 to entry: Averaged power spectrum is expressed in Pa^2.

3.17
median of acoustic pressure
P_n
median value of amplitude values of spectral lines within B_f

Note 1 to entry: Median of acoustic pressure is expressed in pascals (Pa).

3.18
band filter
B_f
band filter located at a centre frequency of 2,25 f_0

Note 1 to entry: Band filter is expressed in hertz (Hz).

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3.19
direct field acoustic pressure
P_0
portion of the RMS acoustic pressure signal arising directly from the ultrasonic driving excitation, at the **operating frequency** of the device

Note 1 to entry: RMS direct field acoustic pressure is expressed in pascals (Pa).

3.20
spectral acoustic pressure
$P(f)$
Fast Fourier Transform of the hydrophone voltage divided by the end-of-cable loaded sensitivity

Note 1 to entry: Spectral acoustic pressure is expressed in pascals (Pa).

3.21
stable cavitation component
P_s
portion of the RMS acoustic pressure signal arising from stable cavitation

Note 1 to entry: The stable cavitation component is expressed in pascals (Pa).

3.22
transient cavitation component
P_t
portion of the RMS acoustic pressure signal arising from transient cavitation

Note 1 to entry: The transient cavitation component is expressed in pascals (Pa).

3.23
voltage
$u(t)$
instantaneous voltage measured by analyser

Note 1 to entry: Voltage is expressed in volts (V).

3.24
voltage spectrum
$U(f)$
Fast Fourier Transform of the voltage

Note 1 to entry: Voltage spectrum is expressed in volts (V).

3.25
frequency spacing
Δf
distance of spectrum samples of a Fast Fourier Transform

Note 1 to entry: Frequency spacing is expressed in hertz (Hz).

3.26
indexed frequency
f_k
frequency of index k at which the Fast Fourier Transform is evaluated

Note 1 to entry: f_k $(k – 1)$ Δf, where k = 1, 2, ..., N_{cap}.

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4 List of symbols

f	frequency
f_k	**indexed frequency**
f_0	**operating frequency**
f_s	**sampling frequency**
$M_L(f)$	**end-of-cable loaded sensitivity**
N_{av}	**number of averages**
N_{cap}	number of points captured in a waveform
t_{cap}	capture time
$P(f)$	**spectral acoustic pressure** (a function of frequency)
$P_0(f)$	**direct field acoustic pressure**
$P_s(f)$	**stable cavitation component**
$P_t(f)$	**transient cavitation component**
$u(t)$	voltage (a function of time)
$U(f)$	voltage spectrum (a function of frequency)
L_{CN}	**cavitation noise level**
P_{ref}	**reference sound pressure**
$\overline{P^2}(f)$	**averaged power spectrum**
P_n	**median of acoustic pressure**
B_f	**band filter**
T_{av}	**averaging time for cavitation** measurement
Δf	frequency spacing

5 Measurement equipment

5.1 Hydrophone

5.1.1 General

It is assumed throughout this document that a **hydrophone** is a device which produces an output voltage waveform in response to an acoustic wave. Specifically, for the case of a sinusoidal acoustic wave, the **hydrophone** shall produce an output voltage proportional to the acoustic pressure integrated over its electro-acoustically active surface area. Assuming that spatial variations in the acoustic pressure field over this active surface area are negligible, the **hydrophone** may then be assumed to be a point sensor and the acoustic field pressure may be described by Equation (1):

$$P(f) = U(f) / M_L(f) \tag{1}$$

where $P(f)$ is the amplitude of the acoustic field pressure, $U(f)$ is the amplitude of the voltage, and $M_L(f)$ is the **end-of-cable loaded sensitivity** of the **hydrophone** (defined also as an amplitude for the purposes of this document). All parameters are expressed as a function of **frequency** and follow the convention of only designating the magnitude of frequency-dependent quantities, disregarding their phase angle.

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5.1.2 Calibration of hydrophone sensitivity

The **hydrophone** shall be calibrated such that $M_L(f)$, the **end-of-cable loaded sensitivity** of the **hydrophone**, is known for any frequency or frequency component for which an acoustic pressure value is reported.

NOTE In some cases **cavitation** measurements can be made in relative terms, in which case a calibration to determine $M_L(f)$ is not necessary. See 5.2.1.3.

5.1.3 Hydrophone properties

5.1.3.1 Acoustic pressure range

The **hydrophone** and any associated electronics shall be suitable for the maximum pressure of the environment, and shall be at minimum suitable for an RMS acoustic pressure up to 600 kPa.

5.1.3.2 Bandwidth of the hydrophone

The bandwidth of the **hydrophone** should be according to 5.1.2, such that variations in $M_L(f)$, the **end-of-cable loaded sensitivity** of the **hydrophone**, may be compensated for by the cavitation measurement scheme, such as in 5.2.1.4.

5.1.3.3 Directional response

The **hydrophone** shall have an approximately spherical directivity. In order to achieve this, for an **operating frequency** below 100 kHz the hydrophone should have an effective diameter less than a quarter wavelength. This guideline may be relaxed above 100 kHz because of the potential difficulty in achieving such a small effective diameter in a package that can withstand the cleaning environment; however, there is the corresponding increase in measurement uncertainty and the user should attempt to account for it.

5.1.3.4 Cable length

A connecting cable of a length and characteristic impedance which ensure that electrical resonance in the connecting cable does not affect the defined bandwidth of the **hydrophone** or **hydrophone-assembly** shall be chosen. The cable shall also be terminated appropriately.

To minimize the effect of resonance in the connecting cable located between the **hydrophone**'s sensitive element and a preamplifier or waveform digitizer input, the numerical value of the length of that cable in metres shall be much less than $50/(f_0 + BW_{20})$ where f_0 is the **operating frequency** in megahertz and BW_{20} is the -20 dB **bandwidth** of the **hydrophone** signal in megahertz.

Attention should be paid to the appropriateness of the output impedance of the **hydrophone**/amplifier in relation to the input impedance of the connected measuring device.

5.1.3.5 Measurement system linearity

The user shall ensure that the voltage output of any preamplifier or amplifier is linear over the range used. This shall be done by obtaining the maximum voltage output within which the response is linear within 10 %, and providing necessary adjustments to gain, such as may be available from gain control settings on the preamplifier or amplifier.

5.1.4 Hydrophone compatibility with environment

Environmental conditions such as temperature or the chemistry of the environment shall be within the hydrophone manufacturer's stated range of operating conditions.

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Differences between the calibration conditions for the hydrophone and the measurement conditions shall be considered to the extent that they may affect the measurements. For example, for **relative cavitation measurements** made at the same temperature with hydrophones of identical construction, it may not be necessary to determine how the sensitivity of the hydrophone changes between the calibration and measurement conditions. However, for absolute measurements the change in hydrophone sensitivity with temperature shall be known, and corrected for in accordance with IEC 62127-3:2007.

5.2 Analyser

5.2.1 General considerations

5.2.1.1 General

The analyser is an instrument that converts $u(t)$, the time-domain voltage waveform provided by the **hydrophone**, to a measurement of **cavitation** activity. 5.2.1 describes several considerations that are independent of the measuring method. Following that, several independent methods are described in 5.2.2 to 5.2.3

5.2.1.2 General considerations: sampling rate

If the analyser utilizes digital recording of $u(t)$, let $u(t_m)$, designate this sampling with t_m designating the discrete points in time captured, with m = 1 ... N_{cap} where N_{cap} is the **size of the capture buffer**. The interval in time between successive samples shall be uniform, and the **sampling frequency** f_{s} shall be at least a factor of two (2) higher than the highest frequency component of interest in the signal. An anti-aliasing filter with a cutoff frequency of at most half of the sampling frequency shall be used to filter out higher frequency components.

The **size of the capture buffer** (N_{cap}) shall also be known (the duration of waveform capture in units of seconds is then $N_{\text{cap}}/f_{\text{s}}$).

5.2.1.3 General considerations: averaging time

T_{av}, the period of time over which the analyser averages results to report **cavitation** activity, shall be known either from a user-defined setting on the analyser or obtained from the manufacturer. For an analyser utilizing digital recording of a waveform $T_{\text{av}} = N_{\text{av}} \times N_{\text{cap}} / f_{\text{s}}$.

See Annex B for examples.

5.2.1.4 General considerations: calibration

For **relative cavitation measurements** performed with the same or identical hydrophones, the measurements may be in terms of voltage only. For all other cases, the measurement shall take account of $M_{\text{L}}(f)$, the **end-of-cable loaded sensitivity** of the **hydrophone** in one of two ways:

1) If variation in $M_{\text{L}}(f)$ is expected to be negligible throughout the frequency range of interest, results shall be scaled by a factor of $M_{\text{L}}(f_0)$, where f_0 is the **operating frequency** of the ultrasound. In this case, the user shall assess the uncertainty in the measurement due to residual deviations in $M_{\text{L}}(f)$ from $M_{\text{L}}(f_0)$ across the frequency range of the measurement.
2) $u(t_m)$ shall be digitally recorded if $M_{\text{L,dB}}(f)$ varies by more than 2 dB over the reported bandwidth of the cavitation signal. $U(f_m)$, its Fast Fourier Transform (FFT), shall be computed and digitally stored for $m < \frac{N_{\text{cap}}}{2}$ (only the single-sided spectrum is saved). Equation (1) shall then be used to calculate the spectral acoustic pressure:

$$P(f_m) = U(f_m) / M_{\text{L}}(f) \quad (2)$$

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NOTE For the purposes of this document, only the magnitude of the Fast Fourier Transform is used.

5.2.2 Specific measurement method: transient cavitation spectrum at $f = 2{,}25 f_0$

In this method, the FFT of $u(t)$ is computed as in 5.2.1.4. The **operating frequency** f_0 is scanned in the spectrum. The noise in a frequency band at the 2,25 fold of the operating frequency f_0 is analysed and a **cavitation noise level** L_{CN} is calculated. The **cavitation noise level** L_{CN} is an indication of **transient cavitation** activity. Further details are provided in Annex B and Annex C.

5.2.3 Specific measurement method: broadband transient and stable cavitation spectra

In this method the FFT of $u(t)$ is computed, noise is subtracted, and a broadband calibration of the **hydrophone** provides a broadband determination of $P(f)$ using Equation (2). A computer algorithm then determines the relative RMS contributions of the applied field, **transient cavitation**, and **stable cavitation** to the acoustic pressure spectrum, and reports these as P_0, P_t, and P_s, respectively. Further details are provided in Annex D.

5.3 Requirements for equipment being characterized

5.3.1 Temperature and chemistry compatibility with the hydrophone

The cleaning environment shall be checked to make sure that its expected temperature range and chemistry are compatible with the hydrophone specifications.

5.3.2 Electrical interference

The user shall perform reasonable checks that electrical interference is not significantly affecting the measurements. These checks should include comparing the signal when the hydrophone is outside of the cleaning solution to when it is inside the solution. If the signal outside in air is significant compared to the signal with the hydrophone in the tank, there is significant electrical interference.

NOTE It may also be possible to check for electrical interference by shielding the hydrophone from acoustic signals with an acoustically absorbing shell while leaving a water path for electrical conduction in a tank.

6 Measurement procedure

6.1 Reference measurements

6.1.1 Control of environmental conditions for reference measurements

Reference measurements are performed under controlled conditions in order to monitor the stability of an ultrasonic system. Significant care must be taken to document and reproduce critical environmental conditions including:

- settings of the equipment under test;
- water quality – cavitation activity is known to depend on the level of impurities and dissolved gases;
- temperature;
- position and angular orientation of the **hydrophone**;
- water height and position of any objects within the cleaning tank;
- ultrasonic settling time, i.e. the time that the ultrasound has been on (generally expected to be at least five minutes).

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In general, the user shall determine tolerances for each of these conditions when establishing a baseline for future reference measurements. This shall be done by observing the variation of cavitation measurements with variation in these parameters, and specifying the tolerances based on the required repeatability of reference measurements. In the case of **hydrophone** position and water height, it is expected that reproducibility within a quarter wavelength at the operating frequency will be sufficient. See Annex A.

NOTE Higher tolerances may occur when objects are inside of a cleaning vessel.

6.1.2 Measurement procedure for reference measurements

1) The **hydrophone** shall be positioned at the documented user-defined locations and angular orientations for the reference measurement.
2) Analyser settings for the reference measurement shall be reproduced based on documented settings.
3) **Cavitation** activity shall be measured according to one of the methods of 5.2.2 to 5.2.3 and recorded.

6.2 Measurement procedures for in-situ monitoring measurements

In-situ monitoring measurements are performed to monitor **cavitation** while a cleaning tank is in use for cleaning. Uses may include research, process development, or documentation.

The level of control is not expected to be as high as in reference measurements. Nevertheless, the following general procedure should be applied.

1) Document cleaning system settings, analyser settings, and ultrasonic settling time.
2) Document position and angular orientation of the hydrophone.
3) Measure **cavitation** activity according to one of the methods of 5.2.2 to 5.2.3 and record results.

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Annex A
(informative)

Background

A.1 Cavitation in ultrasonic cleaning

Acoustic **cavitation** is one of the main components of the ultrasonic cleaning action and is used, for example, for the cleaning of hard surfaces in ultrasonic baths with a setup such as shown in Figure A.1 or in ultrasonic reactors [3].

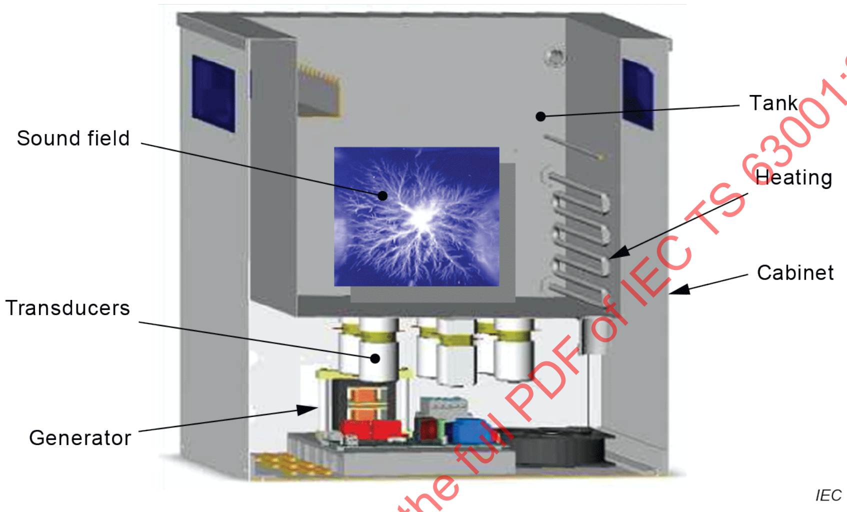

Figure A.1 – Typical setup of an ultrasonic cleaning device

A tank is equipped with ultrasonic transducers, which are driven by an electrical generator with an **operating frequency** adapted to the resonance frequency of the transducers. The tank is filled with a liquid cleaning medium. The temperature of the medium can be influenced by heating elements. Due to the vibration of the transducers, a sound field develops inside the tank.

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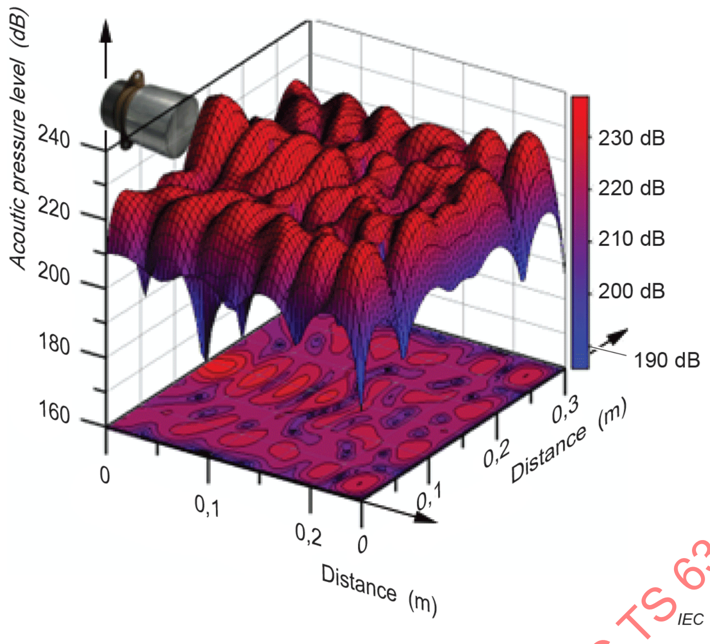

Figure A.2 – Spatial distribution of the acoustic pressure level in water in front of a 25 kHz transducer with reflections on all sides of the water bath (0,12 m × 0,3 m × 0,25 m)

The linear sound field of a small ultrasonic transducer element corresponds approximately to the field of a piston radiator. The radiated waves are totally reflected on the water surface and the tank walls. This results in a three-dimensional standing wave field (Figure A.2) [4]. At the places where the modulus of the rarefactional acoustic pressure exceeds the threshold for transient cavitation, cavities may collapse violently. In this case the maximum bubble radius is three times the initial radius at least and the velocity of the bubble wall is higher than the speed of sound. At lower acoustic pressure bubbles oscillate nonlinearly and gas can diffuse into the bubbles. In both cases, harmonic and subharmonic frequencies of the operating frequency and a broadband noise are produced. The level of these frequency components is shown in Figure A.3. The maximum level is found at the **operating frequency** – in this example at 35 kHz. At low frequencies the acoustic pressure level is limited by the size of the tank [4]. Above the **cavitation** threshold [5-7] broadband noise occurs. This noise level can be corrected by the **hydrophone** frequency response and eventually decreases at high frequencies.

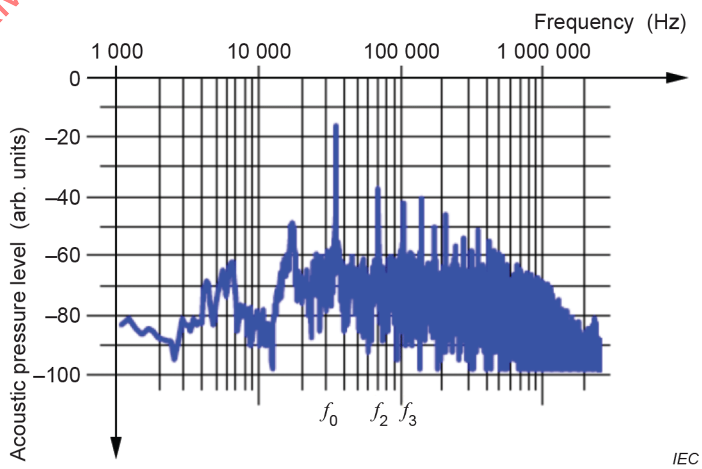

Figure A.3 – Typical Fourier spectrum for sinusoidal ultrasound excitation above the cavitation threshold at an operating frequency of 35 kHz

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The acoustic pressure level of the ultrasonic signal is limited by the nonlinear oscillation of the bubbles. The surface tension and the temperature of the fluid have an effect on the **cavitation**. By Bjerknes forces, the bubbles vibrating in a sound field are moved to the formation of structures (Figure A.4). These structure formations have a settling time which must be taken into account during the measurement. The structure formation is also influenced by the bubble size distribution in the liquid. Therefore, the medium in the ultrasonic tanks was degassed [8] before use.

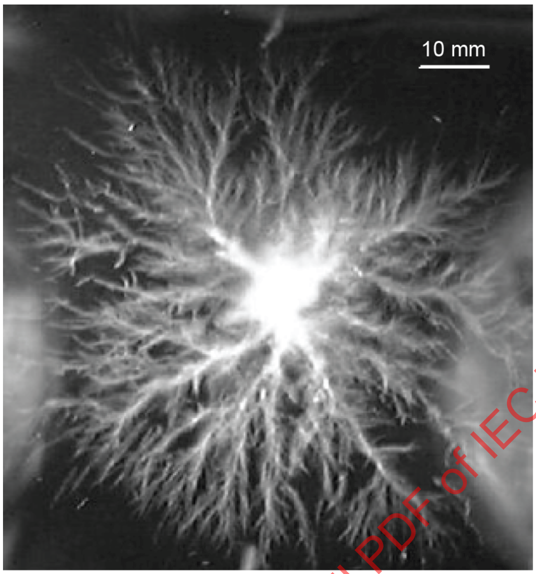

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Figure A.4 – Sketch of cavitation structure under the water surface at an operating frequency of 25 kHz

A.2 Practical considerations for measurements

There are only a few ultrasonic cleaning devices which work with sinusoidal signals. In most modern ultrasonic cleaners, a generator with low output impedance – a voltage source – produces a rectangular voltage. The ultrasonic transducer converts the applied electric power to mechanical power with high efficiency at its resonance frequency. The mechanical power of the transducer is radiated into the coupled fluid. Normally, the nominal value of the active power is preset or adjusted by the user and is controlled by the generator automatically in a closed loop control system. In many cases the amplitude of the signal is additionally modulated. The envelope of the signal often corresponds to the rectified mains voltage (Figure A.5). This modulation should be taken into account in determining the averaging time T_{av} of the measurement.

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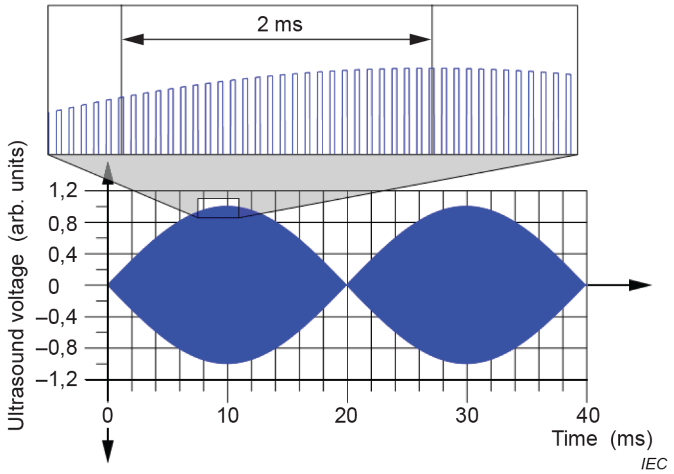

Figure A.5 – Typical rectangular ultrasound signal with a frequency of 25 kHz and 50 Hz double half wave modulation

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The power control is also influenced by the resonance frequency of the system, which is dependent on the level of the medium, the temperature, the amount of goods in the tank and other factors. Therefore the **operating frequency** of the generator changes during operation and should be recorded.

Because of the stochastic behaviour of the **cavitation** activities, some kind of averaging should be applied.

The result of the signal processing gives values to characterize the ultrasound **cavitation** activity.

A.3 Measurement procedure in the ultrasonic bath

The user should define water conditions such as filtration, deionization, gas content, additives, temperature, etc., such that measurements are reproducible. Depending on the requirements of the user, the water temperature should be, for example, between 30 °C and 50 °C and should be degassed until a stable noise level is reached. Depending on the requirements, a) an average or b) a point-determined noise level should be measured for the tank.

1) During the measurement, the **hydrophone** should be moved slowly in a meandering manner through the sonicated volume. During the meandering movement, the noise level should be measured and the mean value should be calculated therefrom. The movement of the **hydrophone** should not destroy the cavitation structures by agitation and should not exceed 10 mm/s.
2) At fixed locations in the sonicated volume, the mean value of the noise level should be measured.

The acoustic centre of the **hydrophone** should always be immersed at least a quarter wavelength. In general, a distance of at least half a wavelength from the walls shall be respected. For example, at a frequency of 25 kHz, the hydrophone should be at least 15 mm deep and 30 mm distant from the wall and the bottom of the tank. At 45 kHz, this corresponds to a depth of 8 mm and a distance of 16 mm.

A.4 Characterization methods that do not utilize the acoustic spectrum

This document describes a method to measure the **ultrasonic** cavitation with a **hydrophone** and an analysis of the resulting noise spectrum described in general in Clauses 5 and 6.

The result of a measurement of the acoustic pressure without spectral evaluation is often ambiguous and therefore not suitable to verify an ultrasound device and is not within the scope of this document.

The measurement of the acoustic pressure results in an instantaneous value, but there are other effects whose measurement gives instantaneous values, which are temporally and causally related to the acoustic **cavitation** induced by the acoustic pressure:

- sonoluminescence or cavitation luminescence [9], whose time-resolved light intensity is directly related to the events of **transient cavitation**, i.e. the flashes of light originate from the collapsing bubbles within less than nanoseconds;
- sonochemiluminescence [10], requiring additionally chemical compounds dissolved in the liquid, which show sonochemically triggered reactions in the solution leading to electronically excited product molecules, returning to their ground state by irradiating the luminescence. An example is the oxidation of luminol in alkaline aqueous solutions, triggered by sonochemically produced OH-radicals which gives blue light delayed up to microseconds after bubble collapses.

These measurements of an instantaneous value are not within the scope of this document.

Besides that, there are other methods for measuring the sum of time-accumulated cavitation, i.e. the dose of some more or less defined effects of ultrasonics:

– erosion of aluminum foils of about 25 µm thickness and not wrinkled (measured by its mass loss or by photometric interpretation) [11-16],

– erosive mass loss of other samples, in principle similar to the standard ASTM G32 [17] but with materials adapted to the cavitation erosion in ultrasonic baths [18];

– optical surface changes by the erosion of specially prepared surfaces, e.g. a steel rod with electroplated multilayers including a final layer of copper, with a thickness in the 1 µm range adapted to the strength of the cavitation [19];

– chemical changes in solutions caused by sonochemical reactions, which, for example, can be made visible by corresponding colour changes [10]. One of the most popular examples is the glassy SonoCheck[1] test tube, but for a critical review see [20];

– other methods not mentioned here.

These measurements of time-accumulated cavitation are not within the scope of this document.

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1 SonoCheck is the trade name of a product supplied by Pereg GmbH. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product. Equivalent products may be used if they can be shown to lead to the same results.

Annex B
(normative)

Cavitation measurement at 2,25f_0

B.1 General

Annex B describes a method to characterize the **cavitation** noise in applications where an **operating frequency** of the ultrasound in a range of 20 kHz to 150 kHz is used. The **transient cavitation** generates the main contribution of the cleaning effect. Typical applications are in the cleaning of, for example, industrial parts, in the laboratory, healthcare, pharmaceutical, medicine, optics, jewelry, and parts of watches.

B.2 Measurement method

A calibrated broadband **hydrophone** satisfying 5.1 for an **operating frequency** up to at least 150 kHz shall be used to measure the acoustic pressure in the fluid of an ultrasound device. It shall be moved slowly and in a meandering fashion through the bath. In the process it generates an output **voltage** $u(t)$. Figure B.1 shows the following steps of the digital signal processing.

If the **hydrophone** is not band-limited, a low-pass filter shall be used as an anti-aliasing filter in the signal path. The analogue signal is then digitized by means of an analogue-to-digital (A/D) converter. The A/D converter should have a **sampling frequency** f_s of at least 1 MHz with a resolution of at least 12 bit. This results in an upper limit frequency of 500 kHz and a dynamic range of 72 dB. The number of values N_{cap} is captured and stored to a digital memory for further processing.

In order to measure the **cavitation** noise in the spectrum between the spectral lines correctly, a window function with high dynamics shall be used. A time-constant weighting is achieved by using the Von-Hann function (raised cosine). The following FFT should have a frequency spacing Δf of

$$\Delta f \le f_0 /100 \quad \text{(B.1)}$$

to achieve enough accuracy. In a practical example with N_{cap} = 8 192 and f_s = 1 MHz, the capture time is

$$t_{cap} = \frac{N_{cap}}{f_s} = 8192\ \mu s \quad \text{(B.2)}$$

and

$$\Delta f = \frac{1}{t_{cap}} \approx 122\ \text{Hz} \quad \text{(B.3)}$$

NOTE The typical application has a cavitation noise level far above the electronic noise of the equipment.

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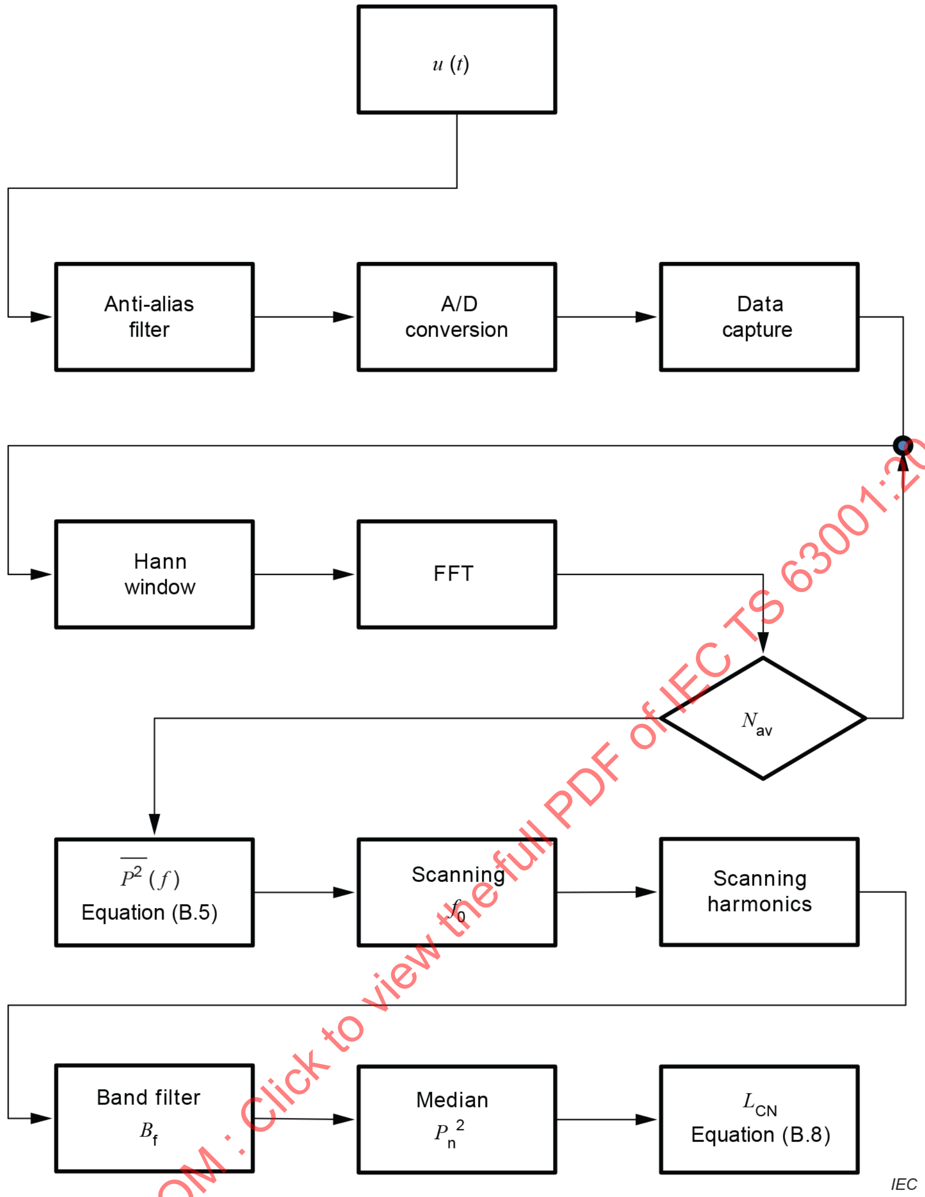

Figure B.1 – Block diagram of the measuring method of the cavitation noise level L_{CN}

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Since the spectral amplitudes of the noise fluctuate strongly and the signal $u(t)$ can occur modulated, it shall be averaged over several spectra. Therefore, the FFT is performed N_{av} times. Due to an efficient use of the captured data, the maximal overlap ability of the Hann window function of 50 % is implemented. Therefore, the base of the sampled values N_{cap} is shifted by $N_{cap}/2$ for each following FFT. The complete time for the measurement t_{av} is

$$t_{av} = (N_{av} + 1) \times t_{cap}/2 \qquad \text{(B.4)}$$

t_{av} shall be close to a multiple of the period of the mains frequency, e.g. 100 ms at 50 Hz. In this case N_{av} = 24. In order to consider the noise power, the squares of the spectral amplitudes $P(f)$ shall be averaged and related to the number of samples N_{cap}. This corresponds to an averaged power spectrum $\overline{P^2}(f)$.

$$\overline{P^2}(f) = 1/N_{av} \sum_{1}^{N_{av}} P^2(f)/N_{cap}^2 \qquad \text{(B.5)}$$

Close to the nominal frequency declared by the manufacturer, the highest amplitude occurs mostly. This **operating frequency** f_0 is now scanned in the spectrum. The spectrum also contains the harmonics of f_0, and because of the nonlinear oscillation of the cavitation bubbles also subharmonic frequencies and their harmonics. All of these harmonics shall be scanned in the spectrum and measured. Since the harmonic waves are usually located at a frequency multiple of $f_0/2$, the noise between the 2- and 2,5-fold harmonic is determined. This corresponds to a **band filter** with the bandwidth B_f.

$$B_f = (2{,}35 - 2{,}15) \times f_0 = 0{,}2 \times f_0 \tag{B.6}$$

and a centre frequency f_c

$$f_c = 2{,}25 \times f_0 \tag{B.7}$$

This frequency range is selected since it proved to be optimal for the measurement. Within this frequency range a number of measured values of the amplitudes of the averaged power spectrum shall be analysed. Since single spectral lines with high amplitudes can be located in this frequency range and in order to prevent them from being weighted disproportionately high, the median value of the amplitudes within B_f shall be selected. The result is the square of the median acoustic pressure P_n^2 of the cavitation noise. If this value is related to the square of the **reference sound pressure** $P_{ref} = 1\ \mu\text{Pa}$, the **cavitation noise level** L_{CN} is obtained as

$$L_{CN} = 10 \log\left(P_n^2 / P_{ref}^2 \right) \tag{B.8}$$

To achieve appropriate values of the result, a fixed normalization factor may be used and documented [21].

With this measuring method, the **operating frequency** and spectrum of the amplitude of the acoustic pressure, the amplitude of the subharmonic frequency and the **cavitation noise level** L_{CN} are measured. This **cavitation noise level** L_{CN} is the measure for the mechanical effect of the cavitation.

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Annex C
(informative)

Example of cavitation measurement at 2,25f_0

As an example, Figure C.1 shows measured values of the **cavitation noise level** L_{CN} for two ultrasound **operating frequencies** as a function of the logarithm of the exciting electrical intensity. Asymptotes were placed on the measured values of the relevant ultrasound frequency. The intersections of the two asymptotes characterize for each ultrasound **operating frequency** the associated cavitation threshold intensities [22]. A proportional range above the ultrasound intensity threshold can be seen for the frequencies 28 kHz and 46 kHz [23, 24]. As the **operating frequency** increases, the intensity at the cavitation threshold increases also. On the other hand, the **cavitation noise level** L_{CN} decreases.

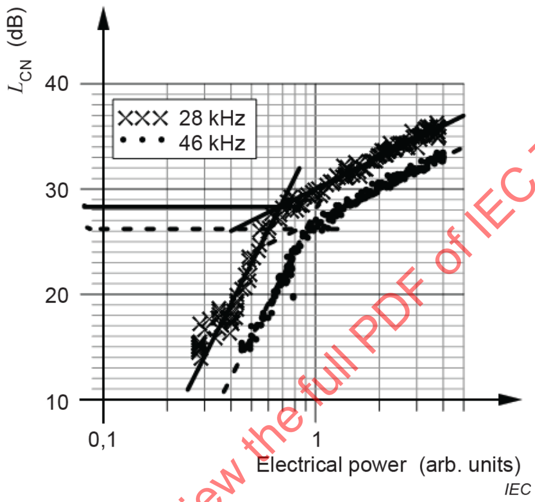

Figure C.1 – Power dependency of the cavitation noise level L_{CN}

NOTE 1 A linear relation between the logarithms of two quantities does not necessarily mean that the two quantities themselves are proportional to each other.

NOTE 2 The transducers for 28 kHz and 46 kHz have the same surface area.

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Annex D
(normative)

Cavitation measurement by extraction of broadband spectral components

D.1 Compensation for extraneous noise

Prior to the start of measurements, compensation for extraneous noise shall be performed. With the direct field off but with the **hydrophone** attached to the analyser, the voltage waveform $u_{\text{noise}}(t_m)$ is recorded. The FFT of $u_{\text{noise}}(t)$, designated as $U_{\text{noise}}(f_m)$, shall be calculated and digitally stored for $m < \frac{N_{\text{cap}}}{2}$. For all subsequent steps, $U(f_m)$ shall be replaced by $U'(f_m) = \sqrt{|U(f_m)|^2 - |U_{\text{noise}}(f_m)|^2}$ in order to correct for the noise. $P(f_m)$ shall then be calculated by substituting $U'(f_m)$ into Equation (2).

D.2 Features of the acoustic pressure spectrum

The acoustic pressure spectrum is shown schematically in Figure D.1.

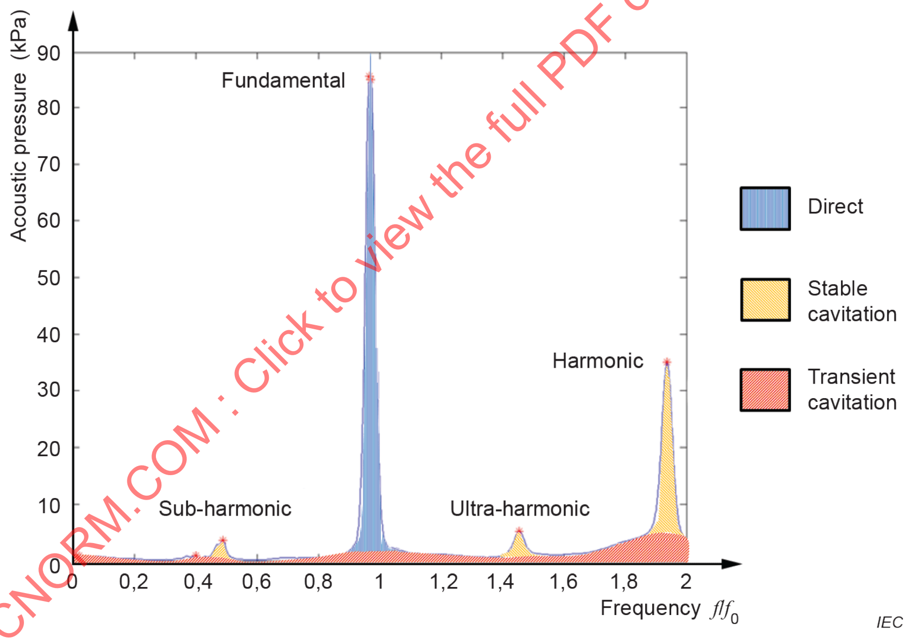

Figure D.1 – Schematic representation of acoustic pressure spectrum $P_{\text{RMS}}(f)$

There are three types of frequency component in the acoustic pressure spectrum [25]:

– the largest spectral peak in the vicinity of f_0, which shall be ascribed to the applied or direct field (shown in blue);

– smaller peaks, which shall be ascribed to **stable cavitation** (shown in yellow);

– broadband noise most prevalent in regions between the peaks, which shall be ascribed to **transient cavitation** (shown in red).

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