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TECHNICAL SPECIFICATION

colour inside

Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

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Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MEASUREMENT OF CAVITATION NOISE IN ULTRASONIC BATHS AND ULTRASONIC REACTORS

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IEC TS 63001 has been prepared by IEC technical committee 87: Ultrasonics. It is a Technical Specification.

This second edition cancels and replaces the first edition published in 2019. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) addition of a new method of measurement: the measurement of integrated broadband cavitation energy between two frequency bounds.

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

Draft	Report on voting
87/804/DTS	87/822A/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

Terms in **bold** in the text are defined in Clause 3.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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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. **Inertial cavitation** is the rapid collapse of bubbles. **Non-inertial cavitation** refers to persistent pulsation of bubbles as a result of stimulation by an ultrasonic field. Both **inertial cavitation** and **non-inertial cavitation** can create significant localized streaming effects that contribute to cleaning. **Inertial cavitation** additionally causes a localized shock wave that can contribute to cleaning and or damage of parts. Both types of cavitation create acoustic signals (**cavitation noise**) which can 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, cleaning equipment, and reactors, as used, for example, for the purposes of industrial process control or for hospital sterilization.

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, equipment, and ultrasonic reactors. It specifies

- the **cavitation** measurement at frequencies between harmonics of the **operating frequency** f_0,
- the **cavitation** measurement derived by integrating broadband cavitation noise energy,
- the **cavitation** measurement by extraction of broadband spectral components.

This document covers the measurement and evaluation of cavitation, but not its secondary effects (cleaning results, sonochemical effects, etc.). Further details regarding the generation of cavitation noise in ultrasonic baths and ultrasonic reactors are provided in Annex A.

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).

Note 2 to entry: As cavitation is a stochastic process, integrating over a sufficiently large t_{av} can be necessary to generate stability of the readings. An example is given in Annex B under Formula (B.4).

3.2
cavitation
formation of vapour cavities in a liquid

3.3
cavitation noise
acoustic signals as measured by a **hydrophone**, arising from the presence of **cavitation** in a liquid, or the interaction of **cavitation** with the **direct field acoustic pressure** signal

3.4
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

3.5
non-inertial 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

3.6
end-of-cable loaded sensitivity
$\underline{M}_\mathrm{L}(f)$
<of a **hydrophone** or **hydrophone assembly**> quotient of the Fourier transformed **hydrophone** voltage-time signal $\mathcal{F}(u_\mathrm{L}(t))$ 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 pulse waveform $\mathcal{F}(p(t))$ 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

$$\underline{M}_\mathrm{L}(f) = \frac{\mathcal{F}(u_\mathrm{L}(t))}{\mathcal{F}(p(t))}$$

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 units of volt per pascal, V/Pa,

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

[SOURCE: IEC 62127-3:2022, 3.7, modified – Only the modulus is considered, Note 1 to entry has been exchanged and Note 2 to entry has been added.] [2]

3.7
end-of-cable loaded sensitivity level
$L_{M_\mathrm{L}}(f)$
<of a hydrophone or hydrophone assembly> twenty times the logarithm to the base 10 of the ratio of the modulus of the **end-of-cable loaded sensitivity** $|\underline{M}_\mathrm{L}|$ to a reference sensitivity of M_ref

$$L_{M_\mathrm{L}}(f) = 20\log_{10}\frac{|\underline{M}_\mathrm{L}(f)|}{M_\mathrm{ref}}\,\mathrm{dB}$$

Note 1 to entry: A commonly used value of the reference sensitivity M_ref is 1 V/μPa.

Note 3 to entry: The **end-of-cable loaded sensitivity level** is expressed in decibels (dB).

[SOURCE: IEC 62127-1:2022, 3.26, modified – In the definition, a different symbol is used and "quotient" has been replaced with "ratio".

3.8
hydrophone
transducer that produces electric signals in response to pressure fluctuations in water

[SOURCE: IEC 60050-801:2021, 801-32-26] [1]

3.9
hydrophone assembly
combination of **hydrophone** and **hydrophone pre-amplifier**

[SOURCE: IEC 62127-3:2022, 3.13] [2]

3.10
number of averages
N_{av}
number of waveforms captured and averaged in a **cavitation** measurement

3.11
operating frequency
f_0
driving frequency of ultrasound generator

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

3.12
relative cavitation noise 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** can be assumed to be identical in both cases

3.13
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).

3.14
size of the capture buffer
N_{cap}
total number of points captured at a time by a digital waveform recorder

3.15
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).

3.16
cavitation noise level
L_{CN}
level calculated from the cavitation noise at frequencies between harmonics of f_0

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

3.17
integrated broadband cavitation noise energy
E_{IBCN}
cavitation noise energy integrated between two identified frequency bounds, f_u and f_l

Note 1 to entry: Commonly expressed in units of V^2s^{-1}.

3.18
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]

3.19
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 units of Pa^2.

3.20
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).

3.21
band filter
B_f
band filter located at a centre frequency which is between harmonics of f_0

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

3.22
centre frequency
f_c
centre frequency of the band filter B_f

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

3.23
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).

3.24
spectral acoustic pressure
$P(f)$
discrete 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).

3.25
non-broadband cavitation component
P_{nb}
portion of the RMS acoustic pressure signal arising **from non-inertial cavitation**

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

3.26
broadband cavitation component
P_b
portion of the RMS acoustic pressure signal arising from **inertial cavitation**

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

3.27
voltage
$u(t)$
instantaneous voltage measured by analyser

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

3.28
voltage spectrum
$U(f)$
discrete Fourier transform of the voltage

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

3.29
window function
$w(n)$
amplitude weighting function used in the discrete Fourier transform

3.30
frequency spacing
Δf
distance of spectrum samples of a discrete Fourier transform

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

4 List of symbols

f	frequency
f_0	**operating frequency**
f_l	lower frequency limit used on the calculation of the **integrated broadband cavitation noise energy**
f_s	**sampling frequency**
f_U	upper frequency limit used on the calculation of the **integrated broadband cavitation noise energy**
E_{IBCN}	**integrated broadband cavitation noise energy**
$M_L(f)$	**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**
$P_{nb}(f)$	**non-broadband cavitation component**
$P_b(f)$	**broadband 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**

f_c **centre frequency**

t_{av} **averaging time for cavitation measurement**

Δf **frequency spacing**

$w(n)$ **window function**

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** can then be assumed to be a point sensor and the acoustic field pressure can be described by Formula (1):

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

where $P(f)$ is the spectral acoustic 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 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.

NOTE The traditional concept of the **hydrophone** is of a nominally point-like measurement device which responds both to the direct field and the signals generated from cavitation bubbles. However, alternative devices have been used and will possibly be developed in future where the details of the construction of the device have been designed to specifically measure the **cavitation** signal. An example of this device is covered in Annex D, where an implementation for measurement of the **integrated broadband cavitation noise energy** is described. For such devices, it is possible that concepts of **hydrophone** sensitivity and directional response are not directly transferrable.

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 5.2.1.4.

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 in accordance with 5.1.2, such that variations in $M_L(f)$, the **end-of-cable loaded sensitivity** of the **hydrophone**, can 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 $50/(f_0 + W_{20})$ where f_0 is the **operating frequency** in megahertz and W_{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** and 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 can 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.

Differences between the calibration conditions for the hydrophone and the measurement conditions shall be considered to the extent that they can affect the measurements. For example, for **relative cavitation noise measurements** made at the same temperature with hydrophones of identical construction, it can be unnecessary 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 62127-3:2022.

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 5.2.4.

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 $m = 1, \ldots, N_{\text{cap}}$ 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. Consideration should be taken of any shockwave components of the signal in assessing the sampling frequency. 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_{cap}/f_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 $t_{av} = N_{av} \times N_{cap} / f_s$. See Annex B for examples.

5.2.1.4 General considerations: calibration

For **relative cavitation noise 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 $M(f)$, the **end-of-cable loaded sensitivity** of the **hydrophone**, in one of two ways.

1) If variation in $M_L(f)$ is expected to be negligible throughout the frequency range of interest, results shall be scaled by a factor of $M_L(f_0)$, 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 $M_L(f)$ from $M_L(f_0)$ across the frequency range of the measurement.
2) $u(t_m)$ shall be digitally recorded if $L_{M_L}(f)$ varies by more than 2 dB over the reported bandwidth of the cavitation signal. $U(f_m)$, the **voltage spectrum** as computed from its discrete Fourier transform (DFT), shall be computed and digitally stored for $m < \frac{N_{cap}}{2}$ (only the single-sided spectrum is saved). Formula (2) shall then be used to calculate the spectral acoustic pressure $P(f_m)$:

$$P(f_m) = U(f_m) / M_L(f) \tag{2}$$

NOTE For purposes of this document only the magnitude of the discrete Fourier transform is used.

5.2.2 Specific measurement method: inertial cavitation spectrum measurement at frequencies between harmonics of f_0

In this method, the DFT 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 between the harmonics of the operating frequency f_0 is analysed and a **cavitation noise level** L_{CN} is calculated. The **centre frequency** f_c of the frequency band is defined as $f_c = f_0 \times \left(\frac{n}{2} + 0{,}25\right)$, where n is an integer.

The **cavitation noise level** L_{CN} is an indication of **inertial cavitation** activity. Further details are provided in Annex B.

5.2.3 Specific measurement method: Measurement of integrated broadband cavitation noise energy between two frequency bounds

In this method, the DFT of $u(t)$ is computed, and the energy between two specific frequency limits, f_l and f_u, is integrated and, following subtraction of noise, used to derive a value of the **integrated broadband cavitation noise energy** (E_{IBCN}). Through appropriate choice of the upper and lower frequency limits of the spectral integration, this quantity is primarily related to the degree of **inertial cavitation** activity. Further details of this measurement can be found in Annex D.

NOTE With knowledge of the variation in the sensitivity of the device between f_l and f_u, the **integrated broadband cavitation noise energy** can be converted to $Pa^2\ s^{-1}$.

5.2.4 Specific measurement method: cavitation noise measurement by extraction of broadband spectral components

In this method the DFT of $u(t)$ is computed, noise is subtracted, and a broadband calibration of the **hydrophone** provides a broadband determination of $P(f)$ using Formula (2). A computer algorithm then determines the relative RMS contributions of the **direct field acoustic pressure**, **broadband cavitation component**, and **non-broadband cavitation component** to the acoustic pressure spectrum, and reports these as P_0, P_b, and P_{nb}, respectively. Further details are provided in Annex F.

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 is also 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. Critical environmental conditions shall be documented and reproduced, 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);
- the type and quantity of any additives added to promote wetting of the surfaces of the ultrasonic system and **hydrophone** in order to aid degassing.

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. Although ideally position repeatability within 1/10 of a wavelength should be achieved, in many cases practical considerations such as oscillations of the water surface justify a relaxation of this recommendation

NOTE Higher tolerances can 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 in accordance with one of the methods of 5.2.2 to 5.2.4 and recorded.

6.2 In-situ monitoring measurements

In-situ monitoring measurements are performed to monitor **cavitation** while a cleaning tank is in use for cleaning. Uses can 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 in accordance with one of the methods of 5.2.2 to 5.2.4 and record results.

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].

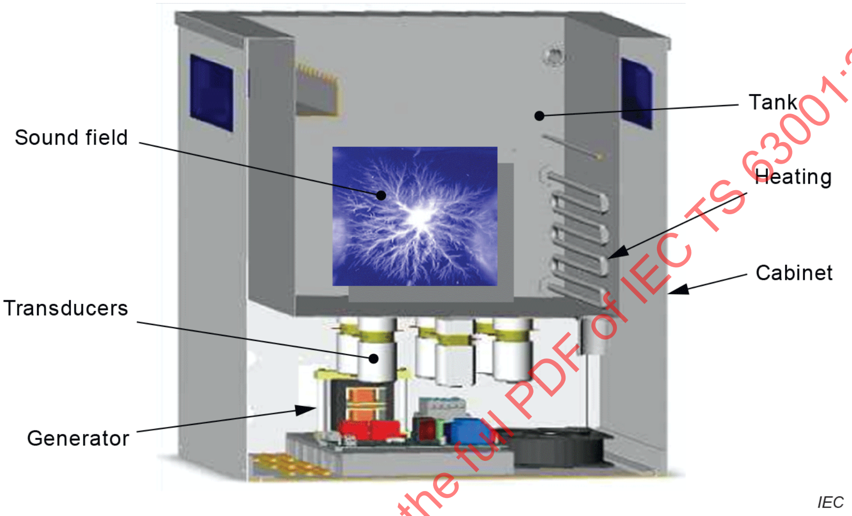


Figure A.1 – Typical setup of an ultrasonic cleaning device

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.

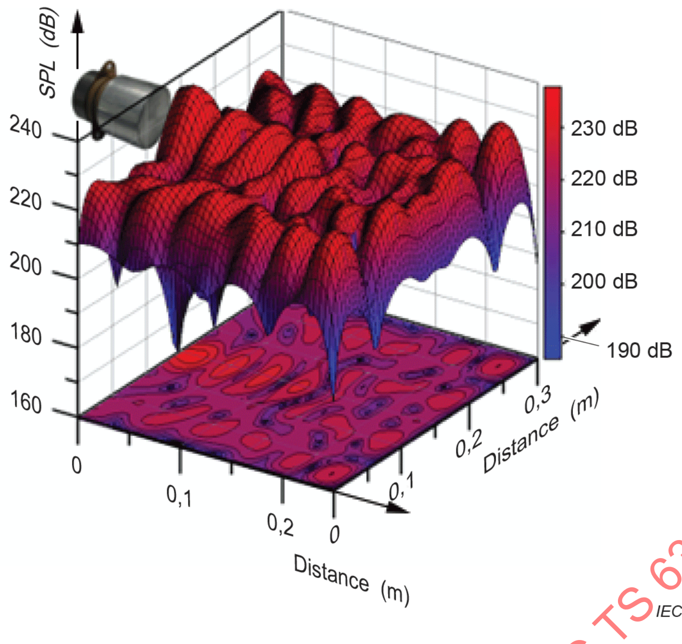


Figure A.2 – Spatial distribution of the acoustic pressure level in water in front of a 35 kHz transducer with reflections on all sides of the water bath (0,12 m × 0,3 m × 0,25 m)

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 inertial cavitation, cavities can 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 broad-band 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 [3]. Above the **cavitation** threshold [5], [6], [7] broadband noise occurs. This noise level can be corrected by the **hydrophone** frequency response and eventually decreases at high frequencies.

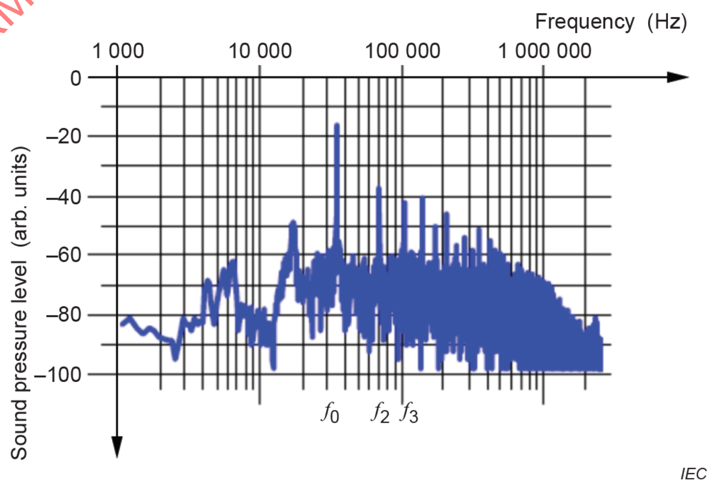
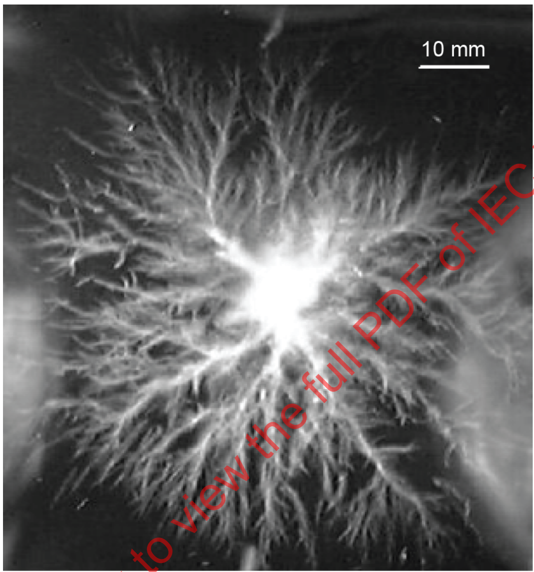


Figure A.3 – Typical Fourier spectrum for sinusoidal ultrasound excitation above the cavitation threshold at an operating frequency of 35 kHz

Figure A.3 illustrates the information contained in the spectral signals, emphasizing the relatively small size of those components associated with cavitation (harmonics, broadband) relative to the direct field at f_0. A study evaluating the performance of various commercial cavitation meters revealed that many do not provide objective measures related to cavitation but are effectively hydrophones responding to the direct field [8]. The measurement procedures described in Annex B, Annex D and Annex F all utilize spectral information.

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 [9] before use.



SOURCE: M. Koechel et al. [22]. Reproduced with the permission of M. Koechel.

Figure A.4 –Photograph 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.

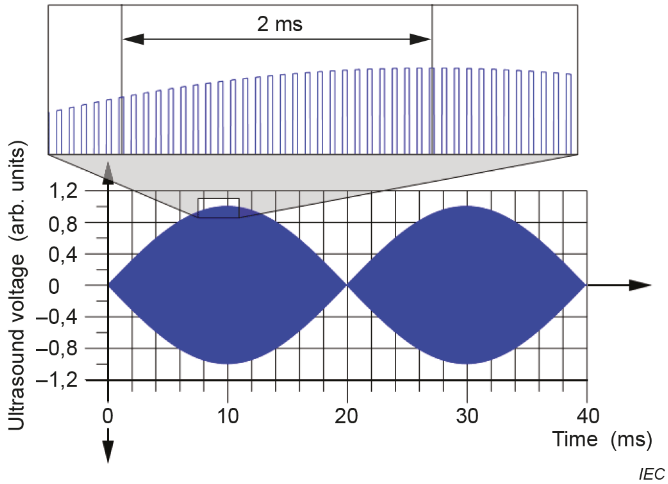


Figure A.5 – Typical rectangular ultrasound signal with a frequency of 25 kHz and 50 Hz double half wave modulation

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 number and properties of the objects in the tank and other factors. Therefore the **operating frequency** of the generator changes during operation and should be measured and recorded digitally, with time referenced to the time of cavitation measurements.

Because of the stochastic behaviour of the **cavitation** activities, averaging is usually applied, and the temporal sampling interval over which averaging is performed is defined.

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

A.3 Measurement procedure in the ultrasonic bath

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 steady **cavitation 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 is 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 are 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 [10], whose time-resolved light intensity is directly related to the events of **inertial cavitation**, i.e. the flashes of light originate from the collapsing bubbles within less than nanoseconds;
- sonochemiluminescence [11], 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.

  EXAMPLE 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 in 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 aluminium foils of about 25 µm thickness and not wrinkled (measured by its mass loss or by photometric interpretation) [12], [13], [14], [15], [16], [17];
– erosive mass loss of other samples, in principle similar to the standard ASTM G32 [18] but with materials adapted to the cavitation erosion in ultrasonic baths [19];
– 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 [20];
– chemical changes in solutions caused by sonochemical reactions, which, for example, can be made visible by corresponding colour changes [11];

  NOTE One of the most popular examples is the glassy SonoCheck[1] test tube, but for a critical review see [21].

– other methods not mentioned here.

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

[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 noise measurement between harmonics of f_0

B.1 General

Annex B describes a method to characterize the **cavitation** noise in applications where the cavitation noise is measured between harmonics of the **operating frequency.** The **inertial 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 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. Figure C.2 shows a diagram with an example of the spectral acoustic pressure of an ultrasonic bath with an operating centre frequency of 103,5 kHz indicated by the light blue marking.

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.

To acquire the single power spectra $P^2(f)$, the following generalized discrete Fourier transform is used:

$$P^2(f) = \left| \sum_{n=0}^{N_{cap}-1} p(n) w(n) e^{-j2\pi fn} \right|^2 \quad \text{(B.1)}$$

This also can be acquired by a chosen discrete Fourier transform (DFT) or similar calculation methods, as long as those represent Formula (B.1) consistently.

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). To avoid possible weighting errors to the broadband noise, the following correction factor [23] for the window function $w(n)$ shall be used:

$$G_{noise} = \frac{1}{N_{cap}} \sum_{n=0}^{N_{cap}-1} w^2(n) \quad \text{(B.2)}$$

The following DFT should have a frequency spacing Δf of

$$\Delta f \leq f_0 /100 \tag{B.3}$$

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

$$t_{cap} = \frac{N_{cap}}{f_s} = 8192 \text{ µs} \tag{B.4}$$

and

$$\Delta f = \frac{1}{t_{cap}} \approx 122 \text{ Hz} \tag{B.5}$$

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

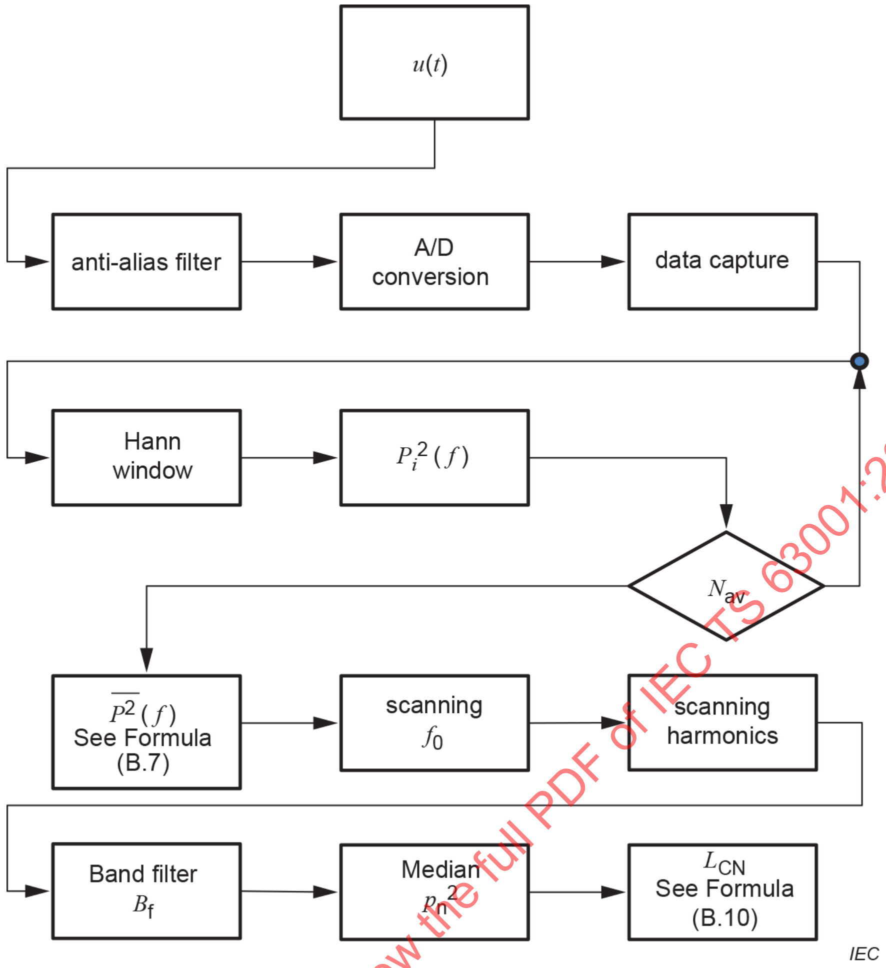


Figure B.1 – Block diagram of the measuring method of the cavitation noise level L_{CN}

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 DFT 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 DFT. The complete time for the measurement t_{av} is

$$t_{av} = (N_{av} + 1) \times t_{cap}/2 \qquad \text{(B.6)}$$

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 $\overline{P^2}(f)$.

$$\overline{P^2}(f) = \frac{1}{N_{av}} \sum_{i=1}^{N_{av}} P_i^2(f) \frac{1}{2G_{noise} N_{cap}} \qquad \text{(B.7)}$$

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 (ultraharmonics). 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 two adjacent harmonics is determined. This corresponds to a **band filter** with the bandwidth B_f

$$B_f = 0{,}2 \times f \tag{B.8}$$

and a centre frequency f_c

$$f_c = f_0 \times \left(\frac{n}{2} + 0{,}25\right) \tag{B.9}$$

where n is an integer. With n = 4 and $f_c = f_0 \times 2{,}25$, a frequency range is selected which proved to be optimal for the measurement of the most ultrasonic baths, but also other values are applicable. 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 of acoustic pressure** P_n of the cavitation noise. If this value is related to the square of the **reference sound pressure** p_{ref} = 1 µPa, the **cavitation noise level** L_{CN} is obtained as [22]

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

The **centre frequency** f_c used for the calculation of L_{CN} shall be documented. 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.

Annex C
(informative)

Example of cavitation noise measurement between harmonics of f_0

As an example, Figure C.1 shows measured values of the **cavitation noise level** L_{CN} for an ultrasound **operating frequency** as a function of the exciting electrical power. The typical characteristic increases in a steep manner at low electrical power and is flatter at higher electrical power. The flat range represents the area, where the cavitation threshold is exceeded [24], [25], [26].

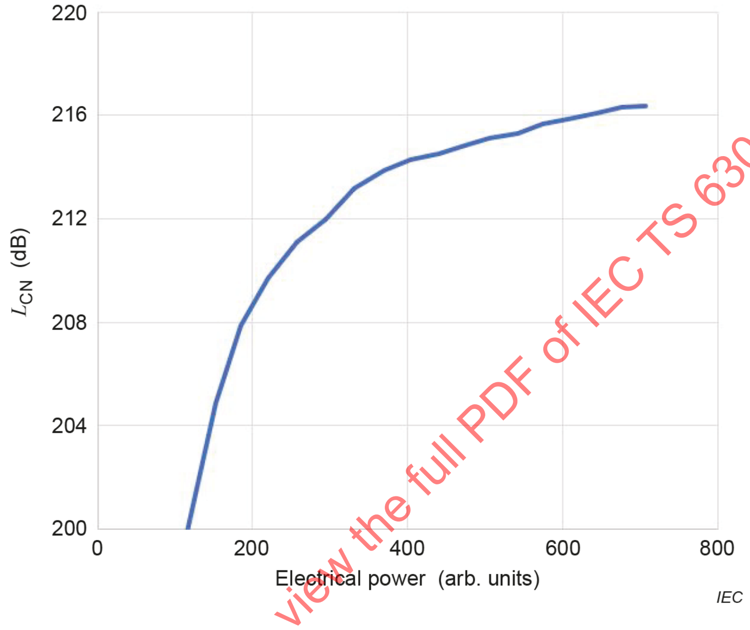


Figure C.1 – Power dependency of the cavitation noise level L_{CN}

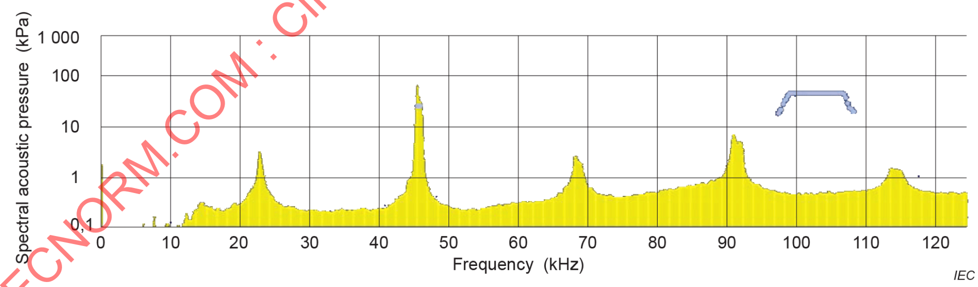


Figure C.2 – Diagram with example of spectral acoustic pressure of an ultrasonic bath with an operating frequency of 46 kHz and its harmonics and sub-harmonics

The cavitation noise is analysed in a frequency range with a centre frequency of 103,5 kHz indicated by the light blue marking.

Annex D
(normative)

Measurement of integrated broadband cavitation noise energy between two frequency bounds

D.1 General

Annex D describes a metric for **inertial cavitation** which involves integrating the broadband energy content of the detector signal between two specific frequency points, f_u (upper) and f_l (lower). The metric can be regarded as complementary to the definition appearing in F.4.3, although the integration does not involve the subtraction of the **non-inertial cavitation** component and so represents a combination of the two. However, signals much greater than the fundamental are predominantly likely to arise from violent **inertial cavitation**. It has been demonstrated that the onset of these elevated frequency signals correlates well with the onset of **inertial cavitation** [26].

D.2 Measurement frequency range

The upper frequency f_u is chosen so that it shall be at least a factor of 10 higher than the operating frequency of the cleaning system (f_0).

D.3 Definition of integrated broadband cavitation noise energy

The measurement involves the evaluation of the temporal voltage waveforms of the detector deployed in the particular application, $u(t)$. Additionally, a corresponding measurement in the absence of ultrasound provides the background noise, $u_{noise}(t)$. Deriving the respective spectra of the two signals, the **integrated broadband cavitation noise energy** (E_{IBCN}) is derived using Formula (D.1):

$$E_{IBCN} = \sum_{k=n}^{k=m} [U(k)^2 - U_{noise}(k)^2] \tag{D.1}$$

where $U(k)$ and $U_{noise}(k)$ are voltage magnitudes of the k-th component of the respective spectra. The upper and lower limits of the summation, n and m, are integer values defining the upper and lower limits of the summation, f_u and f_l.

Annex E
(informative)

Example of measurement of integrated broadband cavitation noise energy between two frequency bounds

Figure E.1 is a schematic view of a device which detects high frequency acoustic emissions from cavitation. The rationale behind the sensor design has been described previously [27], [28] and consists of a thin membrane of the piezoelectric polymer polyvinylidene fluoride or PVDF, wrapped to form a hollow cylinder whose outer surface is 4-mm-thick acoustic absorber which effectively acts as a cavitation shield. The thinness of the membrane increases the measurement bandwidth of the device enabling signals above 5 MHz to be detected. The cavitation shield means that only high-frequency acoustic emissions from cavitation events (potentially both inertial and non-inertial) that occur within the body of the sensor contribute to the sensor signal. Both the properties of the cavitation shield material [27] and the cylindrical shape of the sensor endow the sensor with spatial resolution for signals in the megahertz range, even though the ultrasonic batch or reactor can operate in the 20 kHz to 80 kHz range. The device can be regarded as a particular form of hydrophone and the requirements of Clause 5 and Clause 6 are relevant.

Dimensions in millimetres

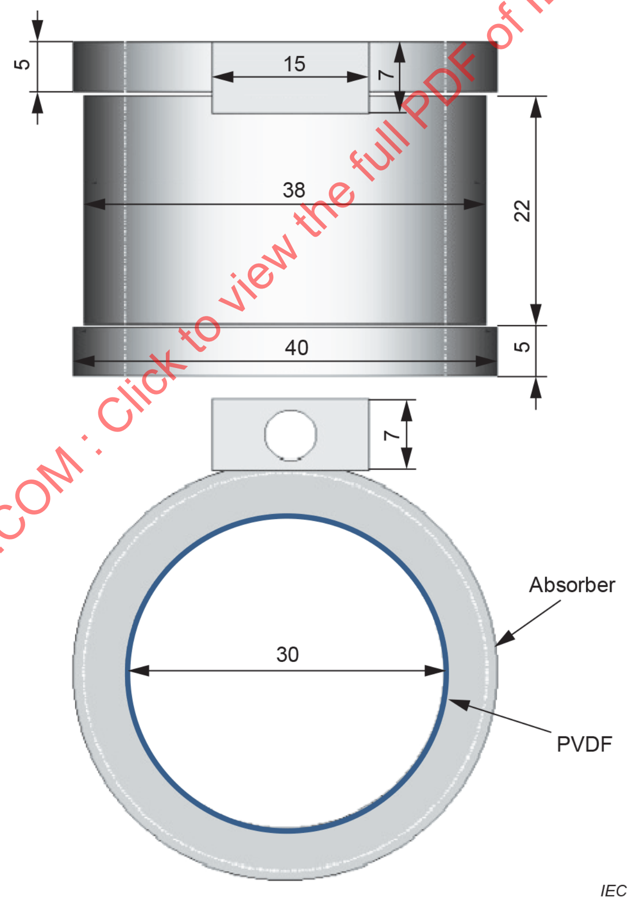


Figure E.1 – Schematic of the cylindrical cavitation hollow cavitation sensor [27], [28]

In use, the sensor is supported by a rigid rod and positioned at the desired location within the ultrasonic cleaning vessel.

Figure E.2 shows acoustic spectra generated by a prototype sensor when immersed in a commercial ultrasonic cleaning device operating at 40 kHz whose electrical power was gradually increased from 5 % to 95 % of full power (nominal vessel power setting). Signal amplitudes in the frequency range f_l = 1 MHz and f_u = 5 MHz have been used to calculate the **integrated broadband cavitation noise energy** whose variation with power is shown in Figure E.3.

A number of publications have investigated use of the cavitation sensor as an objective means of quantifying cavitation [29], [30], [31], [32]. Figure E.4 shows the results of a study on a 40 kHz commercial cleaning vessel with four transducers [29]. Results shown are of a raster scan over the four sources showing the 2D-distribution of the integrated broadband cavitation noise energy. These indicate the spatial resolution of the cavitation sensor and the ability to identify cavitation "hot-spots" caused by overlapping reflections [29]. The results correlated well with a qualitative assessment of the spatial distribution of erosion using a simple aluminium foil test. In this study, electrical signals generated by the cavitation sensor were processed by an electronics module for which f_l = 1 MHz and f_u = 7 MHz.

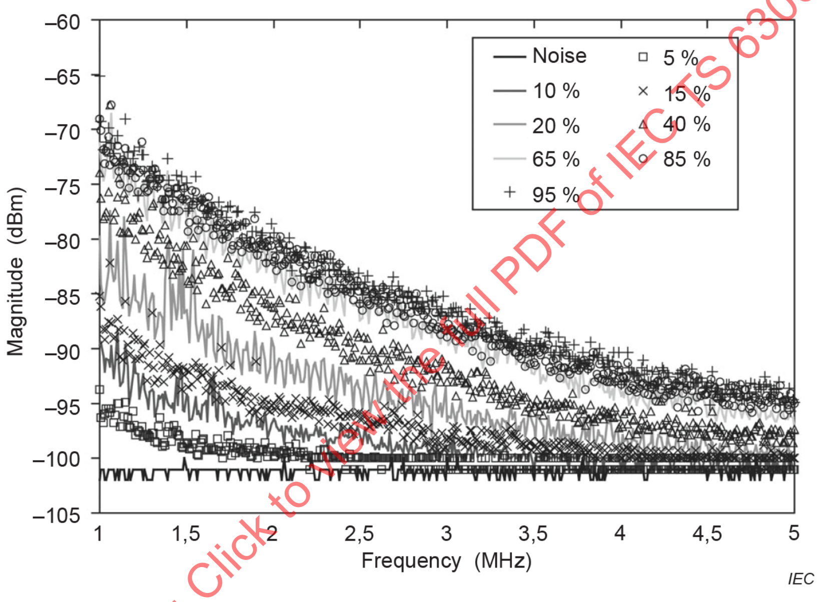


Figure E.2 – High-frequency spectra obtained from the cavitation sensor of the type shown in Figure E.1 [28] for a commercial ultrasonic cleaning vessel operating at 40 kHz whose nominal power setting has been changed from 5 % to 95 % of its full operating power

During the course of the measurement set, temperature increased from 20,3 °C to 21,3 °C and DO_2 (dissolved oxygen content) level increased from 1,95 ppm (parts per million) to 2,86 ppm [28].

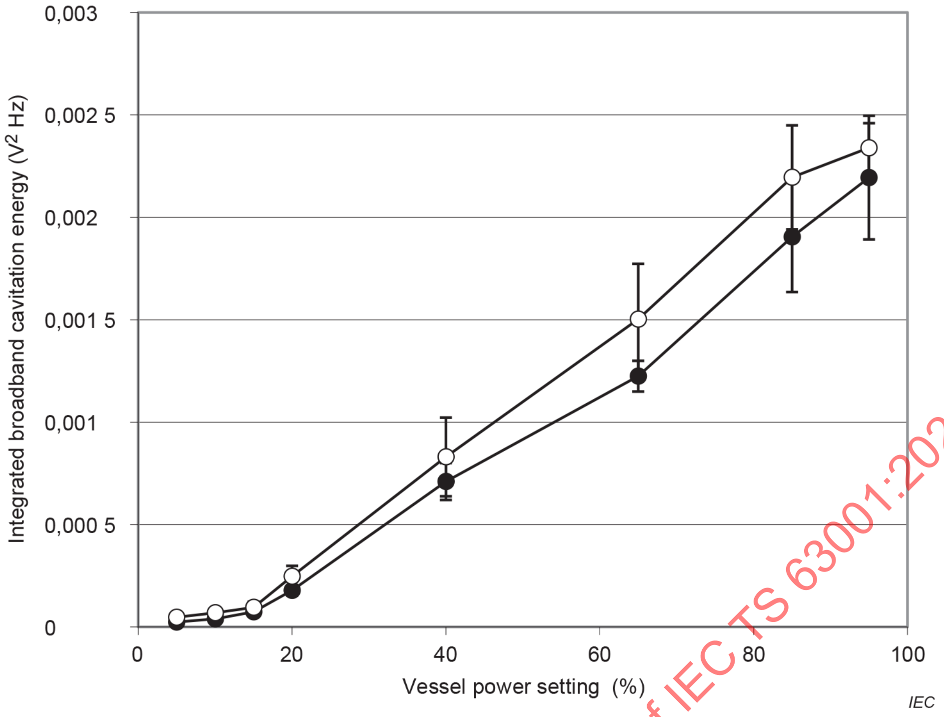


Figure E.3 – Variation in the integrated broadband cavitation energy derived using the cylindrical cavitation sensor, from the acoustic spectra shown in Figure E.2

Measurements are shown for both “ascending” (•) and “descending” (◦) runs. Uncertainty estimates are the Type A (random) uncertainties expressed at the 95 % confidence level. Values have been corrected for the influence of background noise.

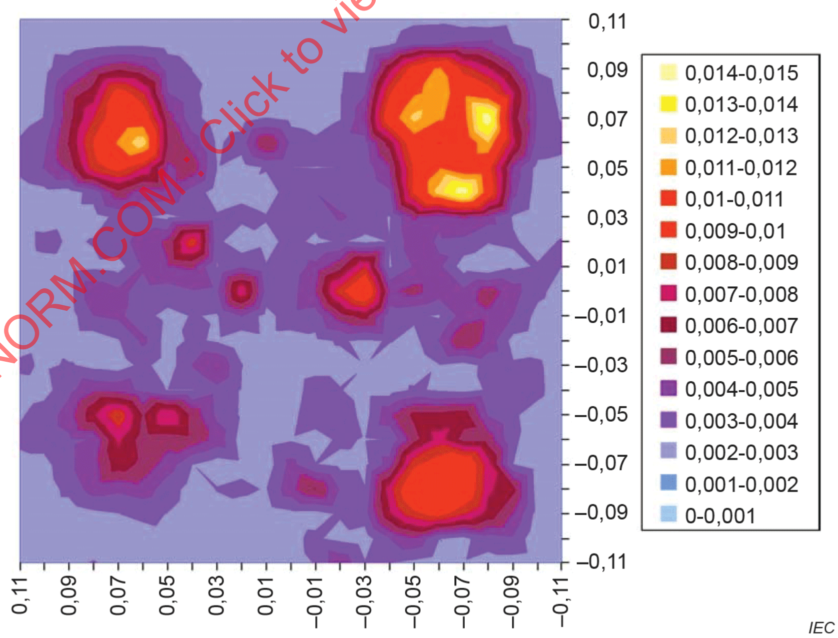


Figure E.4 – Raster scan covering a commercial ultrasonic cleaning vessel with four transducers operating at 40 kHz

The step size (resolution) of the scan was 10 mm. The transducers are seen at the four corners of the raster grid. During the scan, the temperature increased from 30,9 °C to 33,9 °C, and there was slight degassing, with the DO_2 (dissolved oxygen) level decreasing from 5,1 ppm to 4,25 ppm.