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Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

colour inside

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Measurement of cavitation noise in ultrasonic baths and ultrasonic reactors

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,
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- 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. ~~**Transient**~~ **Inertial cavitation** is the rapid collapse of bubbles. ~~**Stable**~~ **Non-inertial cavitation** refers to persistent pulsation of bubbles as a result of stimulation by an ultrasonic field. Both ~~**transient**~~ **inertial cavitation** and ~~**stable**~~ **non-inertial cavitation** ~~may~~ can create significant localized streaming effects that contribute to cleaning. ~~**Transient**~~ **Inertial cavitation** additionally causes a localized shock wave that ~~may~~ can contribute to cleaning and ~~/~~or damage of parts. Both types of cavitation create acoustic signals (**cavitation noise**) which ~~may~~ 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 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.~~
- 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
~~**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

3.5
~~**stable**~~ **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
~~$M_L(f)$~~
$\underline{M}_L(f)$
<of a **hydrophone** or **hydrophone assembly**> ~~modulus~~ quotient of the Fourier transformed ~~**output voltage** $U(f)$~~ **hydrophone** voltage-time signal $\mathcal{F}(u_L(t))$ 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 pressure $P(f)$~~ 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

$$\underline{M}_L(f) = \frac{\mathcal{F}(u_L(t))}{\mathcal{F}(p(t))}$$

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
~~$M_{L,dB}$~~
$L_{M_L}(f)$
<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** ~~$M_L(f)$~~ $|\underline{M}_L|$ 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.~~

$$L_{M_L}(f) = 20\log_{10}\frac{|\underline{M}_L(f)|}{M_{ref}}\text{dB}$$

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 ~~waterborne acoustic signals~~ pressure fluctuations in water

[SOURCE: IEC 60050-801:~~1994~~2021, 801-32-26] [1]

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

[SOURCE: IEC 62127-3:~~2007~~2022, 3.13] [2]

3.10
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~~

3.11
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** ~~may~~ can be assumed to be identical in both cases

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

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 ~~a frequency of 2,25 f_0~~ 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 ~~of 2,25 f_0~~ 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
$P(f)$
Fast 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
stable non-broadband cavitation component
P_s
P_{nb}
portion of the RMS acoustic pressure signal arising **from stable non-inertial cavitation**

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

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

Note 1 to entry: The transient 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
$U(f)$
Fast 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 Fast discrete 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}.

4 List of symbols

f frequency

f_k **indexed 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_s~~ $P_{nb}(f)$	~~**stable**~~ **non-broadband cavitation component**
~~P_t~~ $P_b(f)$	~~**transient**~~ **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}~~ 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** ~~may~~ can then be assumed to be a point sensor and the acoustic field pressure ~~may~~ can be described by Formula (1):

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

where $P(f)$ is ~~the amplitude of~~ the spectral 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 purposes of this document). All parameters are expressed as a