BS EN 62555:2014

BSI Standards Publication

Ultrasonics — Power measurement — High intensity therapeutic ultrasound (HITU) transducers and systems

bsi.

...making excellence a habit.™

National foreword

This British Standard is the UK implementation of EN 62555:2014. It is identical to IEC 62555:2013.

The UK participation in its preparation was entrusted to Technical Committee EPL/87, Ultrasonics.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2014

ISBN 978 0 580 69088 4
ICS 17.140.50

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 May 2014.

Amendments/corrigenda issued since publication

Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 62555

April 2014

ICS 17.140.50

English version

Ultrasonics -
Power measurement -
High intensity therapeutic ultrasound (HITU) transducers and systems
(IEC 62555:2013)

Ultrasons - Mesurage de puissance - Transducteurs et systèmes ultrasonores thérapeutiques de haute intensité (HITU) (CEI 62555:2013)	Ultraschall - Leistungsmessung - Messung der Ausgangsleistung für hochintensive, therapeutische Ultraschallwandler und -systeme (IEC 62555:2013)

This European Standard was approved by CENELEC on 2013-12-24. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

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

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

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

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

CEN-CENELEC Management Centre: Avenue Marnix 17, B - 1000 Brussels

Ref. No. EN 62555:2014 E

Foreword

The text of document 87/538/FDIS, future edition 1 of IEC 62555, prepared by IEC TC 87 "Ultrasonics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62555:2014.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-10-25
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-12-24

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 62555:2013 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 62127-2	NOTE Harmonized as EN 62127-2
IEC 60601-2-62	NOTE Harmonized as EN 60601-2-62

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

Publication	Year	Title	EN/HD	Year
IEC 61161	2013	Ultrasonics - Power measurement - Radiation force balances and performance requirements	EN 61161	2013
IEC/TR 62781		Ultrasonics - Conditioning of water for ultrasonic measurements	-	-

CONTENTS

INTRODUCTION

In ultrasound fields at megahertz frequencies, output power is typically determined by measuring the force on a target using a radiation force balance [1],[2],[3]. However, the relationship between the radiation force and the output power is affected by the focusing or other geometrical aspects of the field, by the type and shape of the target, by the distance of the target from the transducer, by absorption (including ‘shock-loss’) in the water path, and by acoustic streaming currents. Whilst many of these effects are small for typical diagnostic or physiotherapy ultrasound fields, they cannot generally be ignored for HITU fields (particularly for those often referred to as high intensity focused ultrasound HIFU) [4]. Furthermore, in HITU, the quantity of interest is the power incident on the patient rather than the output power at the transducer face. Since it is common to have a water stand-off between the transducer and the patient, attenuation and shock-loss in the water path may be significant and will vary depending upon the chosen distance.

The purpose of this International Standard is to establish standard methods of measurement of ultrasonic power of HITU devices in liquids in the lower megahertz frequency range based on the measurement of the radiation force using a gravimetric balance, and calorimetry (based on the measurement of thermal expansion). This standard identifies the sources of errors and describes a systematic step-by-step procedure to assess overall measurement uncertainty as well as the precautions that should be undertaken and uncertainties that should be taken into account while performing power measurements. Practical guidance is given for the determination of acoustic power from the very wide range of transducer geometries used for HITU. Unlike radiation force approaches in IEC 61161 that deal with “time average power,” other power measurement methods are described in this document.

The structure and content of parts of this International Standard are largely based on IEC 61161:2013 but there are differences that are summarised below. In this standard the prime measurand is considered to be the incident power, and not the output power. Output power is always the quantity of interest in IEC 61161, which specifies that measurements are made with the target placed close to the transducer. However, this may not always be possible for strongly convergent transducers and there are cases where it is more relevant to measure the incident power which reaches a specified surface at some substantial distance from the transducer (this surface may represent the skin surface of the patient, for instance). This extra distance may result in significant nonlinear loss in the water path even at low megahertz frequencies. Consequently, in this International Standard the prime measurand is considered to be the incident power, and not the output power. The incident power may of course be the basis for determining the output power using an appropriate model with its own uncertainties.

ULTRASONICS – POWER MEASUREMENT – HIGH INTENSITY THERAPEUTIC ULTRASOUND (HITU) TRANSDUCERS AND SYSTEMS

1 Scope

This International Standard

- establishes general principles relevant to **HITU** fields for the use of **radiation force** balances in which an obstacle (**target**) intercepts the sound field to be measured;
- specifies a calorimetric method of determining the total emitted acoustic power of **ultrasonic transducers** based on the measurement of thermal expansion of a fluid-filled target;
- specifies requirements related to the statement of electrical power characteristics of **ultrasonic transducers**;
- provides guidance related to the avoidance of acoustic cavitation during measurement;
- provides guidance related to the measurement of HITU transducers of different construction and geometry, including collimated, diverging and convergent transducers, and multi-element transducers;
- provides guidance on the choice of the most appropriate measurement method;
- provides information on assessment of overall measurement uncertainties.

This International Standard is applicable to the measurement of ultrasonic power generated by **HITU equipment** up to 500 W in the frequency range from 0,5 MHz to 5 MHz. **HITU equipment** may generate convergent, collimated or divergent fields.

For frequencies less than 500 kHz, no validations exist and the user should assess the uncertainties of the power measurement and measurement system at the frequencies of operation.

This International Standard does not apply to:

- ultrasound equipment used for physiotherapy, for lithotripsy for general pain relief.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61161:2013, *Ultrasonics – Power measurement – Radiation force balances and performance requirements*

IEC/TR 62781, *Ultrasonics – Conditioning of water for ultrasonic measurements*

3 Terms and definitions

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

3.1
acoustical efficiency

η_a

ratio of the acoustic **output power** from an **ultrasonic transducer** to the **transducer electrical power**

Note 1 to entry: **Acoustical efficiency** is unitless.

3.2
acoustic streaming

bulk fluid motion initiated by a sound field

[SOURCE: IEC 61161:2013, 3.1]

3.3
buoyancy sensitivity

S

ratio of the increase in the buoyancy force on an **expansion target** to the amount of absorbed energy in the absence of thermal losses

Note 1 to entry: This ratio may be temperature dependent.

Note 2 to entry: The **buoyancy sensitivity** for a fluid filled expansion target immersed in water is most conveniently and most accurately determined by calibration using electrical heating (see 7.2.9). It can also be calculated from the product of the **expansion ratio**, the density of the water and the acceleration due to gravity but, in practice, this leads to higher uncertainties.

Note 3 to entry: Since most sensitive balances display weight in grams or milligrams, the **buoyancy sensitivity** is often more conveniently expressed as mass-equivalent **buoyancy sensitivity** in terms of a mass-equivalent unit, such as mg J^{-1}.

Note 4 to entry: **Buoyancy sensitivity** is expressed in Newton per Joule, N J^{-1}.

3.4
expansion ratio

R_V

ratio of the increase in volume of the liquid inside an **expansion target** to the amount of absorbed energy in the absence of thermal losses

Note 1 to entry: Subject to certain assumptions, the **expansion sensitivity** for a fluid-filled **expansion target** can be calculated from the ratio of the volume expansivity of the fluid to its volumetric heat capacity. The ratio may be temperature dependent.

Note 2 to entry: **Expansion ratio** is expressed in cubic metre per Joule, m^3 J^{-1}.

3.5
expansion target

a liquid-filled device specially designed to intercept and absorb substantially all of the ultrasonic field and to undergo thermal expansion

3.6
free field

sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on the sound waves

[SOURCE: IEC 60050-801:1994, 801-23-28, modified – the term no longer contains “sound”]

3.7
high intensity therapeutic ultrasound (HITU) equipment

equipment for the generation and application of ultrasound to a patient for therapeutic purposes with the intention to destroy, disrupt or denature living tissues or non-tissue elements (for example, liquids, bubbles or micro-capsules) and which aims notably at making treatments through actions of ultrasound having mechanical, thermal or more generally physical, chemical or biochemical effects

Note 1 to entry: Essentially **HITU equipment** comprises a generator of electric high-frequency power and a transducer for converting this to ultrasound. In a lot of cases this equipment also includes a targeting and monitoring device.

Note 2 to entry: HITU may as a side effect by its operation induce hyperthermia, however it should not be confused with this technique, which heats much less rapidly and to much lower therapeutic temperatures (in general 42 °C to 50 °C and thermal equivalent times of 0,2 min to 120 min). **HITU equipment** typically causes temperature rises in excess of 55 °C and for much shorter times: alternatively, HITU may also induce bioeffects by non-thermal mechanisms.

Note 3 to entry: This definition does not apply to: ultrasound equipment used for physiotherapy, ultrasound equipment used for lithotripsy or ultrasound equipment used for general pain relief.

[SOURCE: IEC 60601-2-62:2013, 201.3.218, modified – the Note 3 to entry refers to "general pain relief" instead of "dedicated hyperthermia".]

3.8
incident power

P_i

time-average ultrasonic power reaching a specified plane or surface after being emitted by an **ultrasonic transducer** into an approximately **free field,** under specified conditions and in a specified medium, preferably water

Note 1 to entry: **Incident power** is expressed in watt, W

3.9
multi-element transducer

a source of ultrasound comprising two or more spatially separated **ultrasonic transducers**

Note 1 to entry In this context, a single piezoelectric element in a phased array is considered to be an **ultrasonic transducer.**

3.10
nonlinear loss

loss of energy from an ultrasound beam due to the absorption of harmonic components which arise from nonlinear propagation effects

Note 1 to entry: In general, **nonlinear loss** does not occur uniformly throughout an ultrasound field but occurs preferentially where the pressure amplitude is greatest, resulting in a change in the relative distribution of ultrasound energy.

3.11
output power

P

time-average ultrasonic power emitted by an **ultrasonic transducer** into an approximately **free field** under specified conditions in a specified medium, preferably water

Note 1 to entry: **Output power** is expressed in watt, W

[SOURCE: IEC 61161:2013, 3.3]

3.12
radiation conductance

G

ratio of the acoustic **output power** and the squared r.m.s. transducer input voltage.

Note 1 to entry: It is used to characterize the electrical to acoustical transfer of **ultrasonic transducers**.

Note 2 to entry: The r.m.s. drive voltage is used (rather than, for instance, peak-to-peak drive voltage) because its value is less affected by distortion of the applied electrical signal.

Note 3 to entry: This term is not the same as the real part of transducer admittance.

Note 4 to entry: **Radiation conductance** is expressed in siemens, S

[SOURCE: IEC 61161:2013, 3.8, modified –two notes to entry relevant to HITU have been added]

3.13
radiation force
acoustic radiation force

F

time-average force acting on a body in a sound field and caused by the sound field, excluding the component due to **acoustic streaming**

Note 1 to entry: More generally: time-average force (excluding the component due to **acoustic streaming**) in a sound field, appearing at the boundary surface between two media of different acoustic properties

Note 2 to entry: **Radiation force** is expressed in Newton, N

[SOURCE; IEC 61161:2013, 3.4 modified – the second part of the original definition is presented as a note to entry, but without the phrase "or within a single attenuating medium"]

3.14
radiation force target

device specially designed to intercept substantially all of the ultrasonic field and to serve as the object which is acted upon by the **radiation force**

3.15
target

device specially designed to intercept substantially all of the ultrasonic field

3.16
transducer electrical power

P_{el}

rate at which time-average electrical energy is converted by an **ultrasonic transducer** into other forms of energy (typically into heat and the energy of the ultrasonic field)

Note 1 to entry: Electrical power which is reflected from the **ultrasonic transducer** is not part of the **transducer electrical power.**

Note 2 to entry: **Transducer electrical power** is expressed in Watt, W

3.17
ultrasonic transducer

device capable of converting electrical energy to mechanical energy within the ultrasonic frequency range and/or reciprocally of converting mechanical energy to electrical energy

Note 1 to entry: An **ultrasonic transducer** may include connected cables and components for electrical matching.

4 List of symbols

a	radius of a circular ultrasonic source transducer
b_x and b_y	half-dimensions of a rectangular **ultrasonic transducer** in x and y direction, respectively (so that $2b_x$ and $2b_y$ are the transducer's side lengths)
B	change in the buoyancy force acting on an **expansion target** immersed in a sound propagating medium (usually water)
c	speed of sound (usually in water)
d_x and d_y	geometrical focal lengths of a convergent ultrasonic transducer in the x-z and the y-z plane, respectively

d	geometrical focal length of a convergent **ultrasonic transducer, in the case that** $d_x = d_y = d$
C	the volumetric heat capacity
E	the volumetric expansion coefficient
F	**radiation force** on a **target** in the direction of the incident ultrasonic wave
g	acceleration due to gravity
G	**radiation conductance**
h_d	half the diagonal of a rectangular transducer, $h_\mathrm{d} = (b_x^2 + b_y^2)^{1/2}$
h_h	harmonic mean of b_x and b_y, $h_\mathrm{h} = 2 / (1/b_x + 1/b_y)$
k	circular wavenumber ($2\pi/\lambda$)
L	the fraction of **acoustic streaming** momentum recovered by a **target**
M	the time-varying weight of a **target** or **expansion target** as it is displayed by the supporting balance (often in mass-equivalent units)
P	**output power** of an **ultrasonic transducer**
P_el	the **transducer electrical power**
P_i	**incident power** on a **target** or **expansion target**
R_c	radius of curvature of a focused bowl transducer
R_V	the **expansion ratio** of an **expansion target**
s	normalized distance from an **ultrasonic transducer** ($s = z\,\lambda / a^2$)
S	the **buoyancy sensitivity** of an **expansion target**
t_0	the duration of insonation
z	distance between a **target** and the radiating surface of an **ultrasonic transducer** measured along the beam-axis
α	amplitude attenuation coefficient of plane waves in a medium (usually water)
β_x and β_y	focus (half-)angles of a convergent **ultrasonic transducer** in the x-z and the y-z plane, respectively; $\beta_x = \arctan(b_x/d_x)$, $\beta_y = \arctan(b_y/d_y)$ if the transducer is planar and the focal lengths are counted from the planar transducer surface
γ	focus (half-)angle of a circular convergent **ultrasonic transducer**; $\gamma = \arcsin(a/d)$ if the transducer is spherically curved and the focal length is counted from the "bottom" of the "bowl"; $\gamma = \arctan(a/d)$ if the focal length is counted from the plane defined by the rim of the active part of the "bowl" or if the transducer is planar
η_a	the **acoustic efficiency** of an **ultrasonic transducer**
θ	angle between the direction of the incident ultrasonic wave and the normal to the surface of a **target**
ϕ	angle between the direction of the incident ultrasonic wave and the sensitive axis (usually vertical) of a balance
λ	ultrasonic wavelength in the sound-propagating medium (usually water)
ρ	(mass) density of the sound-propagating medium (usually water).

NOTE The direction of the incident wave mentioned above under F and θ is understood to be the direction of the field axis, i.e., it is understood in a global sense rather than in a local sense.

5 Power measurement for HITU equipment

Measurement of **output power** is well established for collimated (and weakly convergent or weakly divergent) ultrasound fields at powers up to 20 W using the **radiation force** method [IEC 61161]. Clause 6 of this International Standard is based on IEC 61161:2013 but some changes are introduced to make it more appropriate for **HITU equipment** which in general is not collimated and has higher **output power**. IEC 61161 specifies that measurements are made with the **target** placed close to the transducer. However, this may not always be possible for strongly convergent transducers and there are cases where it is more relevant to measure the **incident power** which reaches a specified surface at some substantial distance from the transducer (this surface may represent the skin surface of the patient, for instance). This extra distance may result in significant **nonlinear loss** in the water path. Consequently, in this International Standard the prime measurand is considered to be the **incident power**, and not the **output power**. The **incident power** may of course be the basis for determining the **output power** using an appropriate model with its own uncertainties (guidance is given in Annex E). Although the buoyancy change method determines the time-average power incident on the **target** during the insonation time, the **radiation force** method actually determines the turn-on and turn-off power. These two values may be different to each other, and the average of the two is not necessarily equal to the time-average power. In general, insonation time is adjusted as appropriate to the measuring device to account for device limitations.

6 Radiation force on a target

6.1 General

The **radiation force** balance shall consist of a **target** which is connected to a balance. The ultrasonic beam shall be directed vertically upwards or downwards or horizontally on the **target** and the **radiation force** exerted by the ultrasonic beam shall be measured by the balance. The incident ultrasonic power shall be determined from the difference between the force measured with and without ultrasonic radiation. Calibration of the balance can be carried out by means of small precision weights of known mass.

The **target** shall be chosen so as to closely approach one of the two extreme cases, i.e. perfect absorber or perfect reflector.

For a plane incident wave only, the acoustic **incident power** P_i from the **ultrasonic transducer** shall be calculated from the **radiation force** component F on the **target** in the propagation direction using Equation 1 or 2 as appropriate:

For a perfectly absorbing **target**:

$$P_\mathrm{i} = cF \tag{1}$$

For a perfectly reflecting **target**:

$$P_\mathrm{i} = cF\ /\ (2\cos^2 \theta) \tag{2}$$

where

c is the speed of sound in the sound-propagating fluid (water);

θ is the angle between the propagation direction of the incident wave and the normal to the reflecting surface

NOTE 1 The direction of the incident wave mentioned above is understood to be the direction of the field axis, i.e., it is understood in a global sense rather than in a local sense.

The relationship between **radiation force** and **incident power** depends in principle on assumptions about the radiated field and its interaction with the **target** and the measurement tank. For any non-plane wave (e.g. convergent, divergent or arising from multiple simultaneous sources), the correct relationship between **radiation force** and **incident power** shall be determined. The uncertainty in the **incident power** due to the non-plane nature of the field shall be estimated.

In some cases, forces on the **target** due to **acoustic streaming** may be significant compared to the **radiation force**. In order to determine the magnitude of the **radiation force** in these cases, corrective measures shall be taken which may include applying a theoretical correction or the use of a streaming foil close to the **target**. Guidance is given in Annex E. The uncertainty in the **incident power** due to streaming forces shall be estimated.

NOTE 2 The appropriate formulae for certain simple idealised transducer configurations are given in Annex C.

The **incident power** should be measured with the transducer driven in a way similar to its intended clinical use (e.g. continuous wave or with the usual clinical pulsing sequence, provided this is compatible with the time response of the balance).

If it is necessary to use a different pulsing sequence to avoid damage to the **target** or to the transducer, the effect of different thermal loading on the power output of the transducer shall be investigated

Further background information about the requirements in the remainder of Clause 6 can be found in Annex A of IEC 61161:2013.

6.2 Requirements for equipment

6.2.1 Target type

6.2.1.1 General

The use of an absorbing **target** is recommended. The use of a conical reflecting **target** is not recommended in general but may be necessary in some situations.

The **target** shall have known acoustic properties, these being relevant to the details of the relation between ultrasonic power and **radiation force**. (See also A.5.2 of IEC 61161:2013)

6.2.1.2 Absorbing target

An absorbing **target** shall have:

- an amplitude reflection factor of less than 5 %;
- an acoustic energy absorption within the **target** of at least 98 %.

For measurements on a collimated transducer, an absorbing **target** should be orientated at a small angle to the axis of symmetry of the transducer to minimise coherent reflections.

The absorbing material and the design of the **target** shall be chosen to reduce the risk of permanent thermal and mechanical damage by the ultrasound exposure. Temporary changes in the amplitude reflection factor or acoustic energy absorption shall be such that the impact on the overall measured power is less than 2 %, otherwise a correction shall be applied.

6.2.1.3 Reflecting target

A reflecting **target** shall have an amplitude reflection factor greater than 99 %.

The possibility of some part of the ultrasound energy being reflected back to the transducer from the **target** shall be considered and the shape of the **target** shall be chosen appropriately for the transducer geometry.

A conical reflecting **target** is not generally suitable for measurements in convergent or divergent fields and a conical reflecting **target** should not be used to measure convergent transducers, **multi-element transducers** or transducers where $ka < 17,4$ unless specific factors such as transducer geometry make it essential. If use of a conical reflecting **target** is essential due to the shape of the transducer, then the expected relationship between **incident**

power and **radiation force** shall be estimated. Uncertainty due to this relationship shall be included in 6.4.2.

NOTE 1 The exact meaning of the quantity *a* depends on circumstances. For practical transducers, this is the effective transducer radius in accordance with the particular definition in the field of application. In model calculations using a piston approach, it is the geometrical piston radius.

6.2.2 Target diameter

The **target** diameter shall be large enough to intercept at least 98 % of the ultrasound energy reaching the measurement plane. Formulae for estimating the required **target** diameter are given in Annex B.

NOTE Other methods may be used to determine the minimum **target** diameter for an individual transducer design: for instance, modelling or hydrophone measurements.

6.2.3 Balance / force measuring system

The **radiation force** balance may be a gravimetric balance with, therefore, the beam orientation vertical. Alternatively the balance may be of a force feed-back design, allowing the beam to be horizontal. If the balance has been calibrated against mass units, a correct conversion of the balance readings to force values shall be ensured by the manufacturer of the **radiation force** device or by the user.

NOTE Calibration of set-ups with horizontal beam orientation may be carried out using an appropriate balance arm attachment, or by calibration against sources of known acoustic power.

The balance used shall have sufficient resolution for the magnitude of the ultrasonic power to be measured. (See A.5.4 of IEC 61161:2013)

6.2.4 System tank

If a reflecting **target** is used, an absorbing lining of the measuring vessel shall be used so that returning reflections do not contribute to more than 2 % of the overall measured power.

6.2.5 Target support structures

In static-force balances, the structural members supporting the **target** and carrying the **radiation force** across the air-water interface shall be designed to limit the effect of surface tension and buoyancy changes caused by water level fluctuations to less than 2 % of the overall measured power.

6.2.6 Transducer positioning

The **ultrasonic transducer** mount shall allow stable and reproducible positioning of the **ultrasonic transducer** with respect to the **target** in a way that related changes in overall measured power do not exceed 2 %.

6.2.7 Anti-streaming foils

The **target** shall be either provided with an anti-streaming foil to isolate it from **acoustic streaming** in the water path or the measurement process, including data acquisition and analysis, shall be performed in such a way that streaming forces cause no more than a 2 % effect on the overall measured power, otherwise a correction shall be applied.

If an anti-streaming foil is used it shall be positioned close to the **target** and shall not be oriented parallel to the surface of the **ultrasonic transducer**. Its transmission coefficient shall be known from measurement and a correction shall be applied if its influence is more than 2 % of the overall measured power.

NOTE In practice a tilt angle of 5° to 10° has been found to be adequate.

6.2.8 Transducer coupling

The **ultrasonic** transducer shall be coupled to the measurement device such that the impact on the overall measured power is less than 2 %, otherwise a correction shall be applied. (See also A.5.9 of IEC 61161:2013)

6.2.9 Calibration and stability

The force measuring part of the **radiation force** balance shall be calibrated by the use of small weights of known mass.

Changes in the sensitivity of the **radiation force** balance to ultrasonic power shall be monitored by use of an ultrasonic source of known **output power**. The sensitivity shall be tested every year or more frequently if there is any indication that the balance sensitivity to ultrasonic power has changed.

NOTE The sensitivity to ultrasonic power may change due to degradation of the **target** material caused, for instance, by thermal or cavitation damage.

6.3 Requirements for measuring conditions

6.3.1 Lateral target position

The lateral position of the **target** during measurement shall be constant and reproducible to an extent that related changes in overall measured power do not exceed 2 %.

6.3.2 Transducer/target separation

The distance between the **ultrasonic transducer** surface and the **target**, or foil (if used) and **target**, shall be known and reproducible to an extent that possible changes in overall measured power do not exceed 2 %.

6.3.3 Water

When using a **radiation force** balance, the liquid used for the measurements shall be water.

For determining **output powers** above 1 W, only degassed water shall be used. Degassing of water shall be accomplished in a well-defined process such as described in IEC 62781. The water shall be degassed sufficiently to avoid the formation of visible bubbles in the water path or on the surfaces of the transducer or **target**. Measurements shall be discarded if any air bubbles are observed. The total amount of dissolved gas in the water should preferably be < 2 mg/l during all measurements, and may need to be lower in some cases.

The use of degassed water is also recommended for determining **output powers** below 1 W. Bubbles may form on surfaces in gassy water if the temperature of the water increases. Bubbles formation can also be induced by ultrasound and may also form at power levels below 1 W if the beam-area is small enough. Consequently it is recommended to check for the presence of bubbles especially on the transducer and **target** surfaces before, during and after each measurement.

NOTE 1 The gas level required to prevent bubble formation will depend on many factors including acoustic working frequency and maximum negative pressure in the water path. Changing or fluctuating **radiation force** may indicate the formation of bubbles.

NOTE 2 Chemical degassing methods which remove only one or a few gas components (eg the use of Na_2SO_3) are not generally sufficient for HITU measurements. Provided more general methods of degassing are used, monitoring of the oxygen content is simple to do and provides information about the effectiveness of the degassing and the extent of subsequent regassing.

NOTE 3 Filtration of the water can be helpful to avoid or reduce cavitation by removing particulate matter which can act as cavitation nuclei.

6.3.4 Water contact

Before starting the measurements, it shall be ensured that all air bubbles are removed from the active faces. After measurements are completed, the active faces shall again be inspected, and the measurements shall be discarded if any air bubbles are found.

6.3.5 Environmental conditions

The measuring device shall be either provided with thermal isolation or the measurement process, including data acquisition, shall be performed in such a way that thermal drift and other disturbances during the measurement cause no more than a 2 % effect on the overall measured power.

The measuring device shall be protected against environmental vibrations and air flow such that they cause no more than a 2 % effect on the overall measured power.

6.3.6 Thermal drifts

When using an absorbing **target**, an estimate of the thermal effects due to the absorbed sound energy (expansion and buoyancy change) shall be made by recording the measured signal before and after the switch-on and switch-off of the **ultrasonic transducer**.

6.4 Measurement uncertainty

6.4.1 General

An estimation of the overall measurement uncertainty or accuracy assessment shall be determined individually for each set-up used. This assessment should include the following elements.

The uncertainty shall be assessed using the ISO Guide98-3 [5].

6.4.2 Non-planar ultrasound field

The uncertainty in the **incident power** due to the non-plane nature of the field shall be estimated. Unless a better estimate is available, the uncertainty should be estimated as 50 % of the difference between the calculated **incident power** (for instance, calculated according to Annex C) and the value which would result from applying the plane-wave Equations 1 or 2 as appropriate.

6.4.3 Balance system with target suspension

The balance system shall be checked or calibrated using small weights of known mass with the whole system prepared for **radiation force** measurements, the **target** being suspended in water.

This procedure shall be repeated several times with each weight to obtain an indication of the random scatter of results. An uncertainty estimate for the balance calibration factor shall be derived from the results of this calibration and from the mass uncertainty of the weights used.

The results of these checks should be filed in order to enable a judgement of the long-term stability of the balance calibration factor.

6.4.4 Linearity and resolution of the balance system

The linearity of the balance system shall be checked at least every six months as follows.

The measurements described in 6.4.3 shall be made with at least three weights of different masses within the balance output range of interest. The balance readout as a function of input mass can be represented as a graph in accordance with Figure 1. The resulting points of this graph should ideally be on a straight line starting at the origin of the coordinates. If deviations from this line occur, an additional uncertainty contribution shall be derived from them.

Since weights of less than 10 mg are difficult to handle, the balance linearity can also be checked by means of an **ultrasonic transducer** with known properties, activated by various levels of voltage amplitude and thus producing **radiation force** of various magnitudes. In this case the input quantity at the abscissa of Figure 1 is the ultrasonic **output power** of the transducer, and its uncertainty shall be taken into account.

The limited resolution of the balance leads to a power uncertainty contribution that needs to be taken into account in the uncertainty analysis.

6.4.5 Extrapolation to the moment of switching the ultrasonic transducer

In the case of an electronic balance, to obtain the **radiation force** value, the balance output signal is typically recorded as a function of time and extrapolated back to the moment of switching the **ultrasonic transducer** on or off. This extrapolation involves an uncertainty, depending mainly on the amount of scatter in the balance output signal (signal-to-noise ratio). The uncertainty of the extrapolation result shall be estimated by means of standard mathematical procedures in utilizing the regression algorithm.

6.4.6 Target imperfections

The influence of the **target** imperfections shall be estimated using a plane-wave approach such as described in A.7.5 of IEC 61161:2013.

An uncertainty estimate for changes in the **target** properties shall be derived from the results of the stability investigations made with a source of known acoustic power (see 6.2.9). The results of these checks should be filed in order to enable a judgement of the long-term stability of the sensitivity to acoustic power.

6.4.7 Reflecting target geometry

The influence of the reflecting **target** geometry shall be estimated and incorporated into the overall system uncertainty.

6.4.8 Lateral absorbers in the case of reflecting target measurements

The imperfections of the lateral absorbers shall be estimated and incorporated into the overall system uncertainty.

6.4.9 Target misalignment

The influence of **target** misalignment shall be estimated and incorporated into the overall system uncertainty.

6.4.10 Ultrasonic transducer misalignment

The influence of **ultrasonic transducer** misalignment shall be estimated and incorporated into the overall system uncertainty. (See A.7.9 of IEC 61161:2013)

6.4.11 Water temperature

The uncertainty caused by water temperature shall be estimated and incorporated into the overall system uncertainty. (See A.7.10 of IEC 61161:2013)

6.4.12 Ultrasonic attenuation and acoustic streaming

The uncertainty caused by ultrasonic attenuation and **acoustic streaming** shall be estimated and incorporated into the overall system uncertainty. (See A.7.11 of IEC 61161:2013)

6.4.13 Foil properties

If a coupling foil or a shielding foil is used during the **radiation force** measurements, the foil transmission loss as measured or estimated shall be taken into account, as well as any possible effect of the reflected wave on the **ultrasonic transducer**. The uncertainty introduced by these effects shall be assessed individually and incorporated into the overall system uncertainty.

6.4.14 Finite target size

The effect on uncertainty of the finite **target** size shall be determined and included in the overall system uncertainty. (See A.7.13 of IEC 61161:2013)

6.4.15 Environmental influences

The uncertainties caused by environmental vibrations, air flow or temperature variations shall be estimated and incorporated into the overall system uncertainty. (See A.7.16 of IEC 61161:2013)

6.4.16 Excitation voltage measurement

If the excitation voltage applied to the **ultrasonic transducer** is measured and its value is of relevance to the result of the ultrasonic power measurement, its measurement uncertainty shall be estimated and incorporated into the overall system uncertainty. (See also A.7.17 of IEC 61161:2013)

6.4.17 Ultrasonic transducer temperature

If ultrasonic power values measured at different temperatures are to be compared, the dependence of the power on the temperature shall be checked and its influence be taken into account. (See also A.7.18 of IEC 61161:2013)

6.4.18 Nonlinearity

The potential influence of nonlinearities regarding the following shall be assessed and, if necessary, included in the overall system uncertainty:

a) the linearity of the balance system including the **target** suspension;

b) nonlinear contributions due to improperly degassed water;

c) ultrasonic attenuation and **acoustic streaming;**

d) the theoretical **radiation force** relations themselves.

(See A.7.19 of IEC 61161:2013)

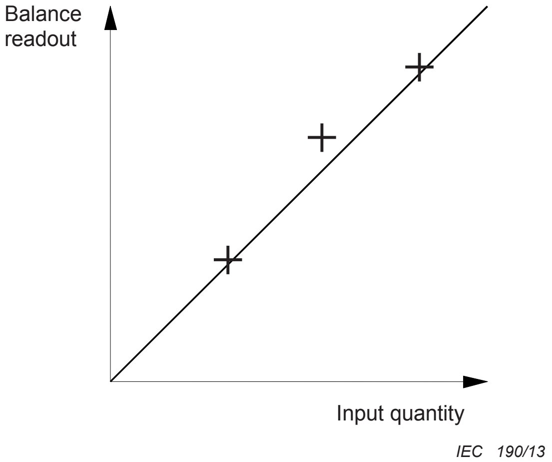
6.4.19 Other sources

Checks should be performed periodically to determine whether the overall uncertainty as specified in 6.4.2 to 6.4.18 using the above guidelines is not influenced by any other sources of random scatter. (See also A.7.21 of IEC 61161:2013)

6.5 Calculation of output power

If a value for the **output power** is required, it shall be determined from the **incident power** by taking into account the effects of attenuation, **nonlinear loss** and **acoustic streaming** in the water path between the transducer and the **target**.

NOTE The ratio of **output power** to **incident power** will generally depend on distance, frequency and **target** geometry; when nonlinear propagation occurs, the ratio will also depend on drive voltage. Further guidance is given in Annex E.



NOTE If linearity is checked by applying small weights of known mass, the input quantity is the mass of the weights used. If the linearity is checked by applying the radiation force of the ultrasonic field emitted by an ultrasonic transducer with known properties, the input quantity is the ultrasonic output power of the transducer.

Figure 1 – Linearity check: balance readout as a function of the input quantity

7 Buoyancy change of a target

7.1 General

The expansion method [6], [7] relies on measuring the change in buoyancy of an **expansion target** caused by thermal expansion of a liquid inside a **target** suspended in a water bath. Provided that no energy is lost from the **target** to the surrounding medium (e.g. by thermal conduction or convection), the change in volume is proportional to the absorbed energy and is independent of focusing or the angle of incidence.

The expansion balance shall consist of an **expansion target** which is connected to a balance which is sensitive to vertical forces. The ultrasonic beam shall be directed at the entry window of the **expansion target** and the change in buoyancy shall be measured by the balance.

NOTE 1 If a vertically acting gravimetric balance is used, it may be convenient to orient the transducer so that it points vertically up or down: this will enable a measurement of **radiation force** simultaneously with the expansion measurement.

The time-averaged **incident power** shall be determined using Equation 3:

$$P_\mathrm{i} = \frac{1}{t_0}\frac{B}{S} \tag{3}$$

where

S is the **buoyancy sensitivity**,

B is the change in the buoyancy force, and

t_0 is the duration of insonation.

In some cases, forces on the **target** due to **acoustic streaming** may be significant compared to the buoyancy change. In order to determine the magnitude of the buoyancy change in these cases, corrective measures shall be taken which may include applying a theoretical correction or the use of a streaming foil close to the **target**. Guidance is given in Annex E. The uncertainty in the **incident power** due to streaming forces shall be estimated.

The **incident power** should be measured with the transducer driven in a way similar to its intended clinical use (e.g. continuous-wave or with the usual clinical pulsing sequence).

NOTE 2 It is not generally necessary to use a different pulsing sequence to avoid damage or to maintain compatibility with the time response of the balance.

Further background information about the requirements in the remainder of Clause 7 can be found in Annex A of IEC 61161:2013.

7.2 Requirements for equipment

7.2.1 Target type

7.2.1.1 General construction

An example **expansion target** is described in Annex D.

The **expansion target** shall consist of a container filled with a liquid which absorbs ultrasound and which expands when heated. One part of the container shall be an entry window which is nearly transparent to ultrasound in the frequency range of interest. The rest of the container should be designed to reduce heat flow into or out of from the absorbing liquid. The **expansion target** shall be suitable for immersion in a water bath and shall have a means for attachment to the balance. The entry window may be positioned vertically, horizontally or at any other convenient orientation.

The size and shape of the **target** shall be chosen appropriately for the transducer being measured. Particular attention should be paid to ensuring that the length of the **target** is sufficient to meet the requirements in 7.2.1.3 at the frequency of interest, and that the amount of energy exiting through the sidewalls of the **target** also permits compliance with 7.2.1.3.

NOTE A cylindrical **target** with an entry window on one end is often convenient, but any other geometry may be used and may be necessary for certain transducer configurations.

7.2.1.2 Absorbing liquid

The characteristic acoustic impedance of the liquid shall be between $1{,}33 \times 10^6$ kg/m^{2}s and $1{,}63 \times 10^6$ kg/m^{2}s. The **expansion ratio** of the liquid shall be known and shall be constant to within 2 % over the temperature range 10 °C to 60 °C.

NOTE 1 This range of acoustic impedance results in an amplitude reflection coefficient of less than 5% consistent with the requirement of 6.2.1.2 for **radiation force** measurement.

NOTE 2 Annex D gives an example of a liquid which meets these requirements.

7.2.1.3 Absorbed energy

An **expansion target** shall absorb at least 98 % of the energy incident on the entry window, otherwise a correction shall be applied.

The absorbing material and the design of the **target** shall be chosen to reduce the risk of permanent thermal and mechanical damage by ultrasound exposure. Temporary changes in the amplitude reflection factor or acoustic energy absorption shall be such that the impact on the overall measured power is less than 2 %, otherwise a correction shall be applied.

7.2.1.4 Reflected energy

The entry window shall have an energy reflection factor of less than 2 % in the frequency range of interest. For measurements on a collimated transducer, the entry window should be orientated at a small angle to the axis of symmetry of the transducer to minimise coherent reflections.

7.2.1.5 Thermal losses

The **expansion target** shall be either provided with thermal isolation or the measurement process, including data acquisition and analysis, shall be performed in such a way that thermal losses from the absorbing liquid to either the water tank or other internal components of the **target** cause no more than a 2 % effect on the overall measured power, otherwise a correction shall be applied.

NOTE Heating of the absorbing liquid next to the entry membrane increases with frequency and may become significant at frequencies above 3 MHz leading to the need to correct for heat loss during the insonation period and subsequent to it [7].

7.2.2 Entry window diameter

The entry window shall be large enough to intercept at least 98 % of the ultrasound energy reaching the measurement plane. Formulae for estimating the required **target** diameter are given in Annex B although, strictly speaking, these formulae apply to **radiation force** measurement.

7.2.3 Balance / force measuring system

The balance shall be sensitive to forces in the vertical direction and shall have sufficient resolution for the change in buoyancy to be measured.

NOTE A longer insonation period will result in a larger change in buoyancy and smaller uncertainty due to balance resolution. However the uncertainty due to thermal losses and extrapolation may increase.

7.2.4 System tank

Since an **expansion target** is absorbing, it is not necessary to use an absorbing lining for the measuring vessel.

7.2.5 Target support structures

In static-force balances, the structural members supporting the **target** and passing through the air-water interface shall be designed to limit the effect of surface tension and buoyancy changes caused by water level fluctuations to less than 2 % of the overall measured power.

7.2.6 Transducer positioning

The **ultrasonic transducer** mount shall allow stable and reproducible positioning of the **ultrasonic transducer** with respect to the **target** in a way that related changes in overall measured power do not exceed 2 %.

7.2.7 Anti-streaming foils

The **expansion target** shall be either provided with an anti-streaming foil to isolate it from **acoustic streaming** in the water path or the measurement process, including data acquisition and analysis, shall be performed in such a way that streaming forces cause no more than a 2 % effect on the overall measured power, otherwise a correction shall be applied.

If an anti-streaming foil is used it shall be positioned close to the **target** and shall not be oriented parallel to the surface of the **ultrasonic transducer**. Its transmission coefficient shall be known from measurement and a correction shall be applied if its influence is more than 2 % of the overall measured power.

NOTE In practice a tilt angle of 5 ° to 10 ° has been found to be adequate.

7.2.8 Transducer coupling

The **ultrasonic** transducer shall be coupled to the measurement device such that the impact on the overall measured power is less than 2 %, otherwise a correction shall be applied.

7.2.9 Calibration

The expansion balance shall be calibrated as a force measuring device by the use of small weights of known mass.

The **buoyancy sensitivity** shall be determined either by use of a collimated ultrasonic source of known **output power** with ka>30 or by an internal electric heating element producing a known heat output. In either case, the determination shall be undertaken once every year or more frequently if there is any indication that the balance sensitivity to ultrasonic power has changed or if the properties of the absorbing liquid are likely to change over time due to water uptake, oxygenation, microbial growth or other causes.

NOTE 1 The **output power** of a collimated source with ka>30 can be measured with uncertainties of less than 5% using a **radiation force target**.

NOTE 2 More information about determining the **buoyancy sensitivity** can be found in D.3 and in [6] and [7].

7.3 Requirements for measuring conditions

7.3.1 Lateral target position

The lateral position of the **target** during measurement shall be stable and reproducible to an extent that related changes in overall measured power do not exceed 2 %.

7.3.2 Transducer/Target separation

The distance between the **ultrasonic transducer** surface and the **target**, or foil (if used) and **target**, shall be known and reproducible to an extent that possible changes in overall measured power do not exceed 2 %.

7.3.3 Water

The liquid used for the measurements shall be water.

For determining **output powers** above 1 W, only degassed water shall be used. Degassing of water shall be accomplished in a well-defined process such as described in IEC 62781. The water shall be degassed sufficiently to avoid the formation of visible bubbles in the water path or on the surfaces of the transducer or **target**. Measurements shall be discarded if any air bubbles are observed. The total amount of dissolved gas in the water should preferably be < 2 mg/l during all measurements, and may need to be lower in some cases.

The use of degassed water is also recommended for determining **output powers** below 1 W. Bubbles may form on surfaces in gassy water if the temperature of the water increases. Bubbles formation can also be induced by ultrasound and may also form at power levels below 1 W if the beam-area is small enough. Consequently it is recommended to check for the presence of bubbles especially on the transducer and **target** surfaces before, during and after each measurement.

NOTE 1 The gas level required to prevent bubble formation will depend on many factors including **acoustic working frequency** and maximum negative pressure in the water path. Changing or fluctuating **radiation force** may indicate the formation of bubbles.

NOTE 2 Chemical degassing methods which remove only one or a few gas components (e.g. the use of Na_2SO_3) are not generally sufficient for HITU measurements. Provided more general methods of degassing are used, monitoring of the oxygen content is simple to do and provides information about the effectiveness of the degassing and the extent of subsequent regassing.

NOTE 3 Filtration of the water can be helpful to avoid or reduce cavitation by removing particulate matter which can act as cavitation nuclei.

7.3.4 Water contact

Before starting the measurements, all air bubbles shall be removed from the active faces. After measurements are completed, the active faces shall again be inspected, and the measurements shall be discarded if any air bubbles are found.

7.3.5 Environmental conditions

The measuring device shall be either provided with thermal isolation or the measurement process, including data acquisition, shall be performed in such a way that thermal drift and other disturbances during the measurement cause no more than a 2 % effect on the overall measured power.

The measuring device shall be protected against environmental vibrations and air flow such that they cause no more than a 2 % effect on the overall measured power.

7.3.6 Thermal drifts

An estimate of the thermal effects due to the flow of energy between the **target** and the surrounding water shall be made by recording the weight of the **target** before and after the switch-on and switch-off of the **ultrasonic transducer**.

7.4 Measurement uncertainty

7.4.1 General

An estimation of the overall measurement uncertainty or accuracy assessment shall be determined individually for each set-up used. This assessment should include the contributions described in 7.4.2 to 7.4.15.

The uncertainty shall be assessed using the ISO Guide [5].

7.4.2 Buoyancy sensitivity

The uncertainty in the **buoyancy sensitivity** shall be evaluated. The factors contributing to the uncertainty in **buoyancy sensitivity** will depend on the method for determining the sensitivity.

7.4.3 Non-planar ultrasound field

The expansion method does not rely on any plane-wave assumptions so there is no uncertainty contribution due to any non-plane nature of the ultrasound field.

7.4.4 Balance system including target suspension

The balance system shall be checked or calibrated using small weights of known mass with the whole system prepared for use, including with the **target** suspended in water.

This procedure shall be repeated several times with each weight to obtain an indication of the random scatter of results. An uncertainty estimate for the balance calibration factor shall be derived from the results of this calibration and from the mass uncertainty of the weights used.

The results of these checks should be filed in order to enable a judgement of the long-term stability of the balance calibration factor.

7.4.5 Linearity and resolution of the balance system

The linearity of the balance system shall be checked at least every six months as follows.

The measurements described in 7.4.4 shall be made with at least three weights of different masses within the balance output range of interest. The balance readout as a function of input mass can be represented as a graph in accordance with Figure 1. The resulting points of this graph should ideally be on a straight line starting at the origin of the coordinates. If deviations from this line occur, an additional uncertainty contribution shall be derived from them.

Since weights of less than 10 mg are difficult to handle, balance linearity can also be checked by means of an **ultrasonic transducer** with known properties, activated by various levels of voltage amplitude and thus producing buoyancy change of various magnitudes. In this case, the input quantity at the abscissa of Figure 1 is the ultrasonic **output power** of the transducer and its uncertainty shall be taken into account.

The limited resolution of the balance leads to a power uncertainty contribution that needs to be taken into account in the uncertainty analysis.

7.4.6 Curve-fitting and extrapolation

In the case of an electronic balance, the balance output signal is typically recorded as a function of time and curve-fitting and extrapolation is required to determine the buoyancy change and compensate for thermal drift and thermal losses from the **target**. This fitting and extrapolation involves an uncertainty, depending mainly on the amount of scatter in the balance output signal (signal-to-noise ratio). The uncertainty of the result shall be estimated by means of standard mathematical procedures in utilizing the regression algorithm.

7.4.7 Water temperature

The uncertainty caused by water temperature shall be estimated and incorporated into the overall system uncertainty.

7.4.8 Ultrasonic attenuation and acoustic streaming

The uncertainty caused by ultrasonic attenuation and **acoustic streaming** shall be estimated and incorporated into the overall system uncertainty.

NOTE In general, attenuation introduces an uncertainty in **output power** measured by buoyancy change but not in **incident power**. Streaming may introduce an uncertainty in both the **incident power** and the **output power**. The uncertainty contribution due to **acoustic streaming** can be estimated, for example, by introducing a streaming foil close to the **target** and comparing results obtained with and without the streaming foil in place.

7.4.9 Foil properties

If a coupling foil or a shielding foil is used during the measurements, the foil transmission loss as measured or estimated shall be taken into account, as well as any possible effect of the reflected wave on the **ultrasonic transducer**. The uncertainty introduced by these effects shall be assessed individually and incorporated into the overall system uncertainty.

7.4.10 Finite target size

The effect on uncertainty of the finite **target** size shall be determined and included in the overall system uncertainty.

7.4.11 Environmental influences

The uncertainties caused by environmental vibrations, air flow or temperature variations shall be estimated and incorporated into the overall system uncertainty.

7.4.12 Excitation voltage measurement

If the excitation voltage applied to the **ultrasonic transducer** is measured and its value is of relevance to the result of the ultrasonic power measurement, its measurement uncertainty shall be estimated and incorporated into the overall system uncertainty.

7.4.13 Ultrasonic transducer temperature

If ultrasonic power values measured at different temperatures are to be compared, the dependence of the power on the temperature shall be checked and its influence be taken into account.

7.4.14 Nonlinearity

The potential influence of nonlinearities regarding the following shall be assessed and, if necessary, included in the overall system uncertainty:

a) the linearity of the balance system including the **target** suspension;

b) nonlinear contributions due to improperly degassed water;

c) ultrasonic attenuation and **acoustic streaming;**

d) increased heat loss from the **target** due to enhanced heating of the absorbing liquid close to the entry window.

7.4.15 Other sources

Checks should be performed periodically to determine whether the overall uncertainty as specified in 7.4.2 to 7.4.14 using the above guidelines is not influenced by any other sources of random scatter.

7.5 Calculation of output power

If a value for the **output power** is required, it shall be determined from the **incident power** by taking into account the effects of attenuation, **nonlinear loss** and **acoustic streaming** in the water path between the transducer and the **target**.

NOTE The ratio of **output power** to **incident power** will generally depend on distance, frequency and **target** geometry; when nonlinear propagation occurs, the ratio will also depend on drive voltage. Further guidance is given in Annex E.

8 Electrical characteristics

8.1 Electrical impedance

The electrical impedance of an **ultrasonic transducer** is frequency dependent and complex. It is typically measured using an impedance analyser and may be stated either as real and imaginary parts or as magnitude and phase. Data may be given at a specified frequency or it may be tabulated or presented graphically over a range of frequencies.

If a value for the electrical impedance is required, it shall be measured with the **ultrasonic transducer** immersed in water. Acoustic reflections within the water tank shall be minimised by the use of acoustic absorbers: the influence of reflections in the impedance value should be checked by varying the position of the **ultrasonic transducer** or the absorbers in the water tank over the range of a few wavelengths. The frequency and the location in the electrical circuit at which the impedance is measured shall be stated (for instance as being at the end of a specified length of cable).

NOTE The impedance may be temperature dependent and consequently, due to transducer self-heating, may be sensitive to the value of the **transducer electrical power** and the duration of excitation.

8.2 Radiation conductance

The **radiation conductance** of an **ultrasonic transducer** is frequency dependent. It is an estimate typically calculated from the **output power** and the square of the r.m.s. drive voltage measured at a specified location in the electrical circuit. Data is usually given at a specified frequency but it may be tabulated or presented graphically over a range of frequencies. It can usefully be applied to a **multi-element transducer**, if all elements are driven with the same drive voltage in a configuration similar to its intended clinical use.

If a value for the **radiation conductance** is required, the r.m.s. drive voltage shall be measured at the same time and under the same excitation conditions as when the **output power** is determined. The frequency and the location in the electrical circuit at which the r.m.s. drive voltage is measured shall be stated (for instance as being at the end of a specified length of cable). It should not be assumed that the drive voltage is sinusoidal: the r.m.s. drive voltage is often not equal to 0,707 x the voltage amplitude.

NOTE 1 The r.m.s. drive voltage is used (rather than, for instance, peak-to-peak drive voltage) because its value is less affected by distortion of the applied electrical signal.

NOTE 2 The **radiation conductance** may be temperature dependent and consequently, due to transducer self-heating, may be sensitive to the value of the **transducer electrical power** and the duration of excitation.

NOTE 3 The **radiation conductance** is not the same as the real part of the radiation admittance of the **ultrasonic transducer** or transducer element.

NOTE 4 This estimate of relative conversion is affected by electrical losses due to impedance mismatch and cables, and acoustical losses due to backing materials and lens losses.

8.3 Efficiency

The determination of **acoustic efficiency** for an **ultrasonic transducer** depends on both electrical and acoustic measurements. Data is usually given at a specified frequency but it may be tabulated or presented graphically over a range of frequencies. It can usefully be applied to a **multi-element transducer**, if all elements are driven in a way similar to its intended clinical use (e.g. continuous wave or with the usual clinical pulsing sequence).If a value of the **acoustic efficiency** is required, the time-average value shall be determined using:

$$\eta_{\mathrm{a}} = P / P_{\mathrm{el}} \tag{4}$$

where

P is the **output power**

P_{el} is the time average **transducer electrical power**.

For the electrical measurements, the **ultrasonic transducer** shall be kept in the same position and environment used to measure the **output power**. The frequency and the location in the electrical circuit at which the **transducer electrical power** is measured shall be stated (for instance as being at the end of a specified length of cable).

Both the powers should be measured with the transducer driven in the same way, a configuration similar to its intended clinical use and drive waveforms (e.g. continuous wave or with the usual clinical pulsing sequence).

NOTE 1 The efficiency may be temperature dependent and consequently, due to transducer self-heating, may be sensitive to the value of the **transducer electrical power** and the duration of excitation.

Many electrical power measurement systems are intended to be used with loads of a specified resistance. The impedance of most **ultrasonic transducers** is likely to differ from the resistance specified. The method chosen for the determination of **transducer electrical power** should be suitable for the impedance of the particular **ultrasonic transducer** under test.

There are several other ways in which efficiency can be defined for an **ultrasonic transducer** or a HITU system. Some of these may be useful for different purposes and are discussed in Annex G.

Annex A
(informative)

Other measurement methods

A.1 Radiation force on a transducer

The possibility of measuring the recoil force on a transducer has been suggested for **HITU equipment**. No specific guidance or requirements are given in this standard. Future amendments may include specific guidance or requirements.

A.2 Calorimetry

Conventional calorimetry can in principle be used to measure power for **HITU equipment**. No specific guidance or requirements are given in this standard. Future amendments may include specific guidance or requirements.

A.3 Hydrophone planar scanning

Power can in principle be measured using planar scanning with hydrophones for **HITU equipment**. No specific guidance or requirements are given in this standard. Future amendments may include specific guidance or requirements. Readers are referred to IEC 62556 [8] and IEC 62127-2 [9].

Annex B
(informative)

Target size

B.1 Non-focusing transducer

In the following, an assessment formula (Equation B.1) is given for the minimum value of the **target** radius *b* which would lead to a **radiation force** which amounts to at least 98 % of the **radiation force** that would exist if the **target** were of infinite cross-sectional size (i.e. giving an error of less than 2 %) [10]. The equation is valid for an absorbing circular **target** in the field of a continuously vibrating, baffled circular plane piston **ultrasonic transducer** of radius *a* in a non-absorbing medium. The formula does not strictly apply to measurements based on buoyancy change so, while it provides a reasonable starting estimate of the required **target** diameter, users should assess its suitability for their own measurements. The formula is:

$$b = a\left[\frac{1}{\left(1 + 0{,}53\,\tau_1 s\right)} + \tau_1 s\right] \qquad \text{(B.1)}$$

with

$$\beta = 0{,}98 + 0{,}01\,\pi k a$$

$$\tau_1 = \tau_0 + \Delta\tau$$

$$\tau_0 = ka\,/\,(2\pi\,(\beta^2 - 1)^{½})$$

$$\Delta\tau = \begin{cases} 0{,}7 & \text{if } ka \le 9{,}3 \\ 6{,}51/ka & \text{if } 9{,}3 \le ka \le 65{,}1 \\ 0{,}1 & \text{if } 65{,}1 \le ka \end{cases}$$

where

z	is the distance between the **target** and the **ultrasonic transducer**;
λ	is the ultrasonic wavelength in the propagation medium;
$k = 2\pi/\lambda$	is the circular wavenumber;
$s = z\,\lambda/a^2$	is the normalized distance between the **target** and the **ultrasonic transducer**.

Equation (B.1) can also be solved for *s*, yielding a maximum value of the normalized distance between the **target** and the **ultrasonic transducer** for a **target** of given radius b. The influence of absorption and **acoustic streaming** is considered separately.

By way of precaution, b should never be reduced below $1{,}5a$, even if this were possible in accordance with the above equation.

Strictly speaking, the above formulae apply to an absorbing **target** but they may also be used to decide whether a reflecting **target** is appropriate for measurements in case of a diverging beam. b should then be understood as the radius of the largest **target** cross-section (in the case of a convex-conical reflector this would be the base of the cone) and z as the distance of that cross-section from the transducer.

B.2 Focusing transducer

In this case, the assessment procedure (taken from [11]) for the minimum value of the radius r of an absorbing circular **target** is different from that in B.1. The criterion is again that the

radiation force is to be at least 98 % of the **radiation force** that would exist if the **target** were of infinite cross-sectional size.

If in the case of a spherically curved transducer, the focal length and the **target** distance are counted from the "bottom of the bowl", d and z as used here need to be derived from them by subtracting the depth of the bowl.

The assessment is valid for the distance range between z/d = 0 and z/d = 2. The necessary **target** radius r/a normalized to the transducer radius is given for four values of z/d as follows:

$$r/a = 1 \quad \text{for} \quad z/d = 0 \tag{B.2}$$

$$r/a = 0{,}5 + 6{,}24\cdot(ka\,\sin\gamma)^{-0{,}885} \quad \text{for} \quad z/d = 0{,}5 \tag{B.3}$$

$$r/a = 12{,}54\cdot(ka\,\sin\gamma)^{-0{,}749} \quad \text{for} \quad z/d = 1 \tag{B.4}$$

$$r/a = 1 + 29{,}1\cdot(ka\,\sin\gamma)^{-0{,}892} \quad \text{for} \quad z/d = 2 \tag{B.5}$$

where

a is the radius of a circular ultrasonic source transducer;

d is the geometrical focal length of a convergent **ultrasonic transducer** measured from the plane defined by the rim of the active part of the transducer;

k is the circular wavenumber, $k = 2\pi/\lambda$

z is the distance between an **ultrasonic transducer** and a **target** measured from the plane defined by the rim of the active part of the transducer;

γ is the focus (half-)angle of a circular convergent **ultrasonic transducer.**

If the actual **target** distance is between two of the above z/d values, the corresponding r/a results are to be interpolated linearly.

NOTE The above assessment does not apply when the transducer has a central hole.

Annex C
(informative)

Formulae for radiation force

C.1 General

The formulae given in this annex may be used to estimate the **incident power, P_i,** on an absorbing **target** from a range of simple idealised transducer types. There is no guarantee that any real transducer will behave like its idealised counterpart, and this introduces a major source of uncertainty when using the **radiation force** method to determine **incident power**. The users should determine for themselves the correct relationship between **incident power** and **radiation force** for each transducer configuration under test, which may be different to any of the equations given here.

This scope of this standard includes transducers of all shapes and geometries. However, the formulae in this annex are mainly for transducers of circular shape or containing individual circular elements. For non-circular geometries, the users should determine for themselves the correct relationship between **incident power** and **radiation force** for each transducer configuration under test.

The use of an absorbing **target** is recommended in this International Standard and no formulae are suggested for any type of reflecting **target**.

C.2 Guidance for focusing transducers

C.2.1 Single spherical segment transducer

$$P_\mathrm{i} = \frac{2Fc}{1+\cos\gamma} \tag{C.1}$$

where

P_i is the acoustic **incident power**;

F is the **radiation force** acting on the absorbing **target**;

c is the sound speed in water;

γ is the focal half-angle of the convergent transducer, γ = arc sin (a/d).

C.2.2 Single spherical zone transducer (single spherical segment transducer with a central circular hole)

$$P_\mathrm{i} = \frac{2Fc}{\cos\gamma_1 + \cos\gamma_2} \tag{C.2}$$

where

γ_1 is a half of the convergent angle of the outside aperture of the transducer;

γ_2 is a half of the convergent angle of the inner hole aperture of the transducer;

C.3 Guidance for multi-element transducers

C.3.1 Focusing array of circular piston elements transducer

If N identical plane-piston transducer elements are placed on a common spherical surface, all beam axes of the elements intersect at the centre of the common spherical surface to construct a focusing array. When every element has the same acoustic power, the total acoustic power P of the array can be calculated using following formula:

$$P_\mathrm{i} = corr \times {N\,F\,c} \bigg/ {\sum_{j=1}^{N} \cos\theta_j} \tag{C.3}$$

where

F is the total **radiation force** acting on the absorbing **target**;

θ_j is the angle included between the main beam axis of the whole array and the beam axis of the jth transducer element, i.e. the incident angle of the beam axis of the jth transducer element to the absorbing **target**;

$corr$ is the correction factor of the plane wave accounting for the diffraction of a single plane-piston transducer, i.e. P_i / cF

$$corr = \frac{1 - J_1(2ka)/ka}{1 - J_0^2(ka) - J_1^2(ka)} \tag{C.4}$$

where

k is the circular wave number;

a is the radius of single transducer;

J is the symbol of Bessel function;

$J_0()$ is the zero order Bessel function;

$J_1()$ is the first order Bessel function.

The curve of $corr(ka)$ is shown in Figure C.1.

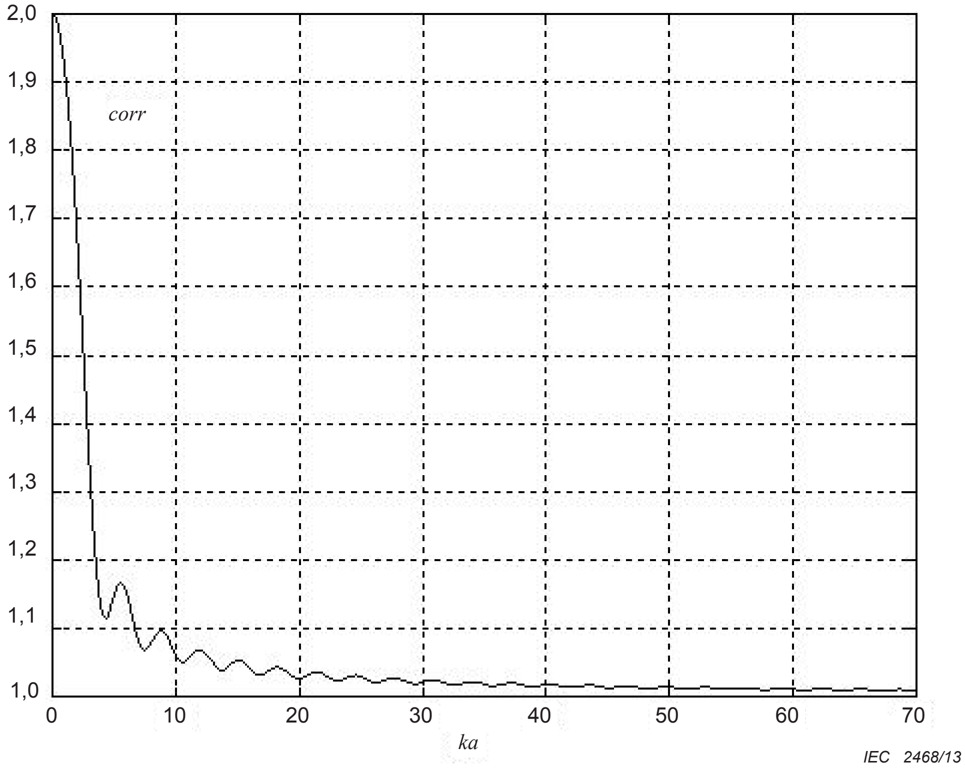


Figure C.1 – Correction factor of plane wave for the acoustic field of a circular plane piston ultrasonic transducer as a function of the product of the circular wavenumber and transducer radius

C.3.2 Focusing array of circular self-focusing element transducer

If N identical focused bowl transducer elements are placed on a common spherical surface and all focuses of the element transducer are at the centre of the common spherical surface, which means that they have a common focus and the same focal length. When every transducer transmits the same acoustic power, the total acoustic power P of the array can be calculated using following formula:

$$P_{\mathrm{i}} = \frac{\dfrac{2NFc}{1+\cos\gamma}}{\sum_{j=1}^{N}\cos\theta_j} \qquad \text{(C.5)}$$

where

F is the total **radiation force** acting on the absorbing **target**;

γ is the focus (half-)angle of a self-focusing transducer element;

θ_j is the angle included between the main beam axis of the whole array and the beam axis of the jth transducer element, i.e. the incident angle of the beam axis of the jth transducer element to the absorbing **target**, degrees or radians.

C.4 Guidance for steerable phased arrays

For the plane wave beam from a steerable phased array:

$$P_{\mathrm{i}} = {Fc}/{\cos\varphi} \tag{C.6}$$

where

F is the total **radiation force** acting on the absorbing **target**;

φ is the angle included between the beam axis and the direction of sensitivity for the **radiation force** balance using the absorbing **target**, e.g. the steering angle.

For a spherically convergent beam from a steerable phased array:

$$P_{\mathrm{i}} = {2Fc}/{\left((1+\cos\gamma)\cos\varphi\right)} \tag{C.7}$$

γ is the focus (half-)angle of a self-focusing transducer element.

C.5 Guidance for moving or modulated sources

No general guidance is given for moving sources. The response of a **radiation force target** to a changing power or to a changing angle of incidence, depends on the timescale of the change compared to the response time of the balance (typically 1 s to 3 s). If the timescale of the change is much shorter than the response time, the measured force at turn-on or turn-off approaches the time-average force; if the timescale of the change is much longer than the response time, the measured force at turn-on or turn-off approaches the instantaneous force at the moment of turn-on or turn-off.

In the specific case of a beam of constant power which is translated over the surface of a **target** without change in the angle of incidence, no additional correction is required as long as the **target** is large enough to intersect at least 98 % of the energy which would be intercepted by an infinite **target** placed at the same distance.

C.6 Guidance for intersecting beams

For N convergent beams intersecting in the field where each has individual focus angle γ_j, steering angle θ_j, and acoustic power P_j , the total **radiation force**, F, is:

$$F = \frac{1}{2c}\sum_j \left(P_j(1+\cos\gamma_j)\cos\varphi_j\right) \tag{C.8}$$

where j = 1, 2.. N

F is the total **radiation force** acting on the absorbing **target**;

φ_j is the angle included between the beam axis of the jth beam and the direction of sensitivity for the RFB using the absorbing **target**, e.g. the steering angle;

γ_j is the focus (half-)angle of a self-focusing transducer element.

In the general case, the total power $\sum_j P_j$ cannot be calculated from the total force. However, if the fraction b_j of the total power is known for each beam, the total **incident power**, $\sum_j b_j P$, can be calculated:

$$P_{\mathrm{i}} = 2F\,c\sum_{j}\left(\frac{1}{b_j(1+\cos\gamma_j)\cos\varphi_j}\right) \tag{C.9}$$

C.7 Guidance for non-focusing transducers

For a single element collimated transducer:

$$P_{\mathrm{i}} = c \quad F\,\frac{1-J_1(2ka)/ka}{1-J_0^2(ka)-J_1^2(ka)} \tag{C.10}$$

which can be approximated by

$$P_{\mathrm{i}} = c \quad F\left[1+\frac{0{,}6531}{2ka}\left(1+\frac{1{,}407}{(ka)^{2/3}}\right)\right] \tag{C.11}$$

C.8 Other geometries.

Information on other geometries (for example, cylindrical inward or outward firing) is not currently offered.

Annex D
(informative)

Expansion method

D.1 General

The principles of the expansion method, sources of uncertainty and an example of an **expansion target** are described by Shaw [6] and are summarised in this annex. A later paper [7] explores measurement at frequencies up to 10 MHz and addresses in detail determination of the **buoyancy sensitivity** by electrical heating and correcting for the effects of heat loss through the entry membrane, also described in this annex.

D.2 Principles

A schematic diagram of an example **expansion target** is shown in Figure D.1. In this example, the transducer and oil-filled **target** are immersed in a water bath with the transducer directed towards the entry membrane of the **target**. The **target** is suspended from a balance and is positioned to intercept the whole of the ultrasound field generated by the transducer.

NOTE Although not used in [6] or [7], it is recommended to configure the experimental arrangement such that it permits the inclusion of a streaming foil placed close to the **target**.

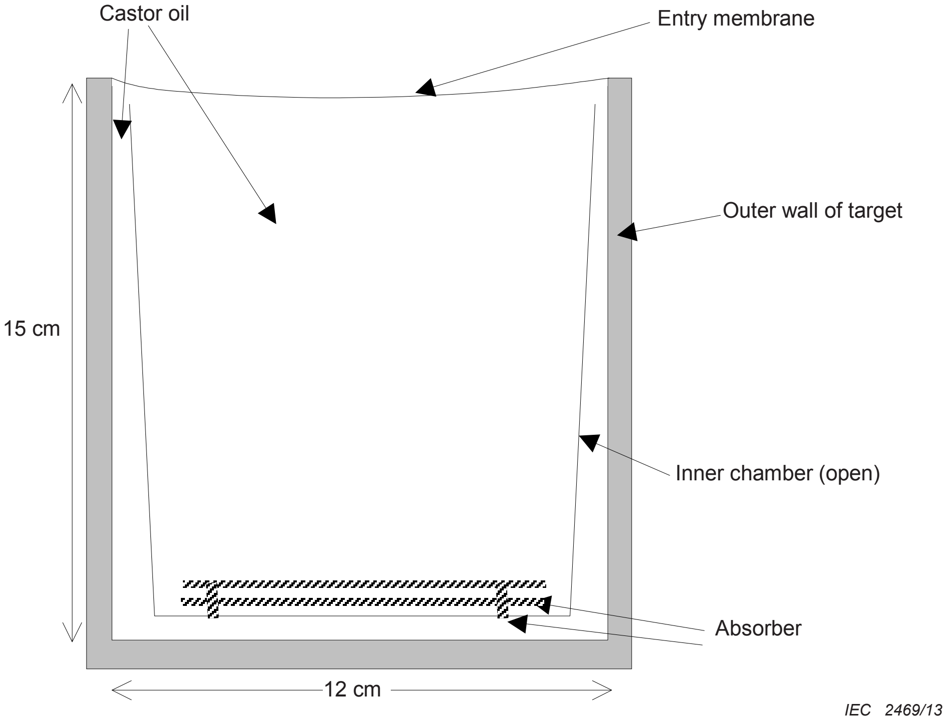
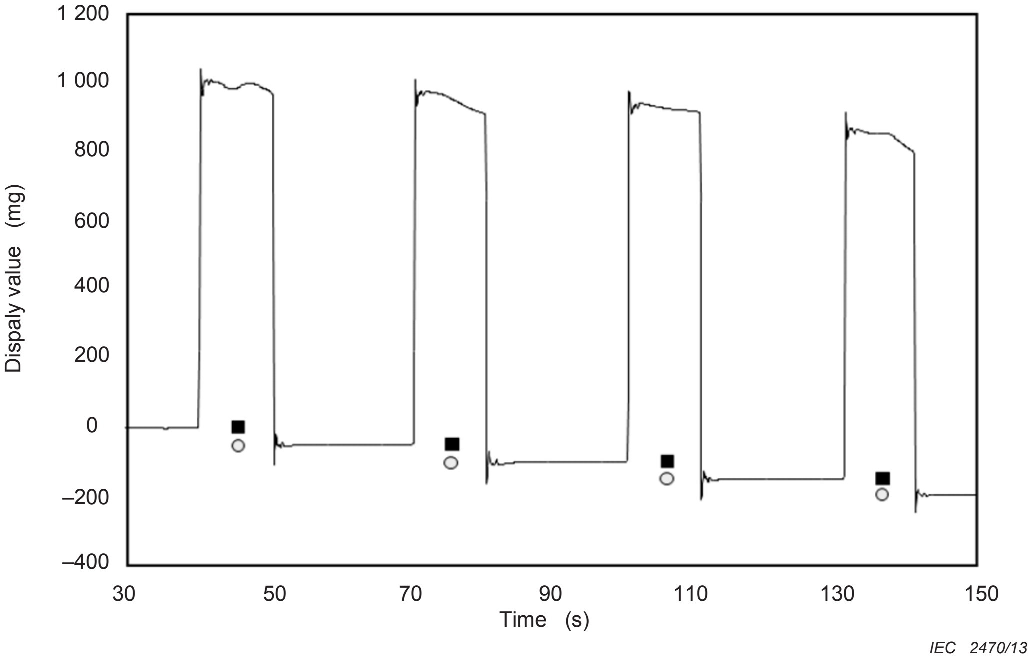


Figure D.1 – Schematic diagram of an expansion target.

An example weight vs. time sequence is shown in Figure D.2 for an **incident power** of approximately 15 W: the ultrasound is absorbed resulting in an instantaneous **radiation force** and a progressive heating of the castor oil. Heating causes either the volume or the internal pressure to increase and the **target** is designed with a thin entry membrane which is transparent to ultrasound and is intentionally not under tension so that the pressure of the oil remains constant and its volume is free to expand. The change in volume results, according to

Archimedes' principle, in an additional buoyancy force acting vertically on the **target** and so the weight registered by the balance decreases. This stepwise decrease following each on-period can be determined from the weight vs. time sequence. In [6], the magnitude of the buoyancy change for each on period was calculated by selecting a section of the weight sequence immediately prior to insonation and a section after insonation (leaving sufficient time for **target** disturbances due to the large **radiation force** to die down). Both sections were extrapolated to the midpoint of the on period as shown in Figure D.2. The appropriate mathematical function to fit to the weight sequences is discussed in D.4.



The ultrasound power is initially off and is turned on at 40 s for 10 s. Filled squares indicate the mass extrapolated forward from the previous off period; open circles indicate the mass extrapolated backwards from the following off period. The buoyancy change for an individual on period is given by the difference between each pair of symbols.

Figure D.2 – Example of weight vs time sequence

The **buoyancy sensitivity**, S, defined as the change in buoyancy per unit absorbed energy, is independent of the volume of the **target** and is given by:

$$S = \frac{B}{P_\mathrm{a}\, t_0} = \frac{\rho_\mathrm{w}\, E}{\rho_\mathrm{oil}\, C} \tag{D.1}$$

where

B is the change in buoyancy force;

P_a is the absorbed acoustic power;

t_0 is the duration of insonation;

ρ_w is the density of water;

E is the volumetric expansion coefficient of the oil;

ρ_oil is the density of the oil;

C is the volumetric heat capacity of the oil.

So, for a known insonation period, the change in the indicated mass is directly proportional to the ultrasound power subject to the following assumptions:

a) The ratio $E/(\rho\ C)$ is constant over the range of temperature occurring inside the **target** at the time the buoyancy change is measured following insonation. It does not matter if the local temperature temporarily exceeds the range where this ratio is constant.
b) The heat lost from the oil to the container or the surrounding water is much less than the absorbed energy.
c) Other sources of heat are much less than the absorbed energy.
d) The ultrasound energy incident on the **target** is completely absorbed in the oil.
e) The water bath remains at a constant temperature and density.
f) The pressure of the oil remains nearly constant.
g) To determine power, as opposed to integrated energy, the power output of the transducer should be constant.

It has been shown [6] that these assumptions can be met at frequencies up to 3 MHz. More recent work [7] has shown that at frequencies above 3 MHz, there is increasing heat loss due to heating of the oil close to the membrane and subsequent energy flux into the water. It is necessary to correct for this heat loss (see D.4).

D.3 Example expansion target

The **target** consisted of a perspex cylinder with an inner diameter of 12 cm and a length of 15 cm; the cylinder is filled with laboratory grade castor oil (absorption coefficient 0,8 dB cm^{-1} MHz$^{-1,7}$). The end of the cylinder facing the transducer is sealed with a plastic membrane of measured thickness 10 µm, the far end with a 5 mm thick perspex plate. The reflectivity of the entry membrane was measured to be less than -30 dB up to 2 MHz and less than –22 dB up to 5 MHz. To provide additional thermal insulation between the heated oil and the walls of the **target**, an open thin-walled chamber is fitted internally. The far end of the inner chamber is fitted with two pieces of acoustic absorber each 2,5 mm thick: at 1 MHz the reflection loss was measured to be –25 dB and the transmission loss –23dB cm^{-1}. These absorbers are surrounded by castor oil to ensure rapid thermal equilibration with fluid. The entire **target** can be suspended directly from a balance or can be fitted to a cradle which allows the transducer to be fitted vertically above the **target**. The balance used had a resolution 1 mg and capacity of 1 200 g: the displayed mass was read continuously *via* an RS232 interface for analysis. A weight was attached to the rear of **target** to ensure it remained negatively buoyant and was stable in the water; liquid crystal thermometers were fitted to the outside of the inner chamber to indicate the general temperature of the oil and monitor changes.

Powers up to 350 W were measured. Under extreme conditions, bubbles could be generated but they were only observed at 0,8 MHz at power levels above 300 W with the focus placed just inside the **target** and with initial oil temperatures above 35 ^{o}C. Streams of bubbles were generated under these conditions but were reabsorbed if the **target** was allowed to cool. No long term change to the **target** performance was observed. In any event, these conditions should not arise in practice as it is intended that the focus should be placed substantially inside the oil volume. Damage to the acoustic window was not observed but may be anticipated following prolonged exposure close to the focus.

D.4 Determination of buoyancy sensitivity

Relevant properties of a specific sample of castor oil are given in Tables D.1 and D.2. The sensitivity may vary with time and may be dependent on the particular sample of oil. However, it is expected to be always essentially invariant with temperature. The absorption coefficient may also vary with time and may be dependent on the particular sample of oil.

The sensitivity at a particular temperature can be determined more simply experimentally by measuring the rate of change of weight of a container of castor oil which is heated electrically whilst suspended in a tank of water. In one example, heat was provided by passing current through a 30 cm length of nichrome wire with a resistance of approximately 33 Ω m^{-1} at room temperature. The ends of the wire were attached to two 2 mm plugs mounted in the base of the **target** and it was twisted into a spiral to fit conveniently. Two methods of analysis have been used. The first method involved calculating the slope of the apparent mass and taking the difference between the slope during the middle 5 s of each on period and average of the slopes before and after that on period. This is the method used by Shaw [6] and has the advantage that the heating time does not need to be well controlled and it is less sensitive to transient changes in the electrical power. In the second method, the analysis is based on total change in apparent mass of the **target** before and after an on period, to determine the average rate of change of mass. This method is closer to the method for measuring acoustic power but demands that the on period is accurately known to calculate the rate of change. In some configurations, the thermal energy stored in the heating element can introduce a systematic bias in the result and should be accounted for [7].

Table D.1 – Selected properties of Acros® Organics[1] castor oil in the range 10 °C to 60 °C

Temperature *T* °C	**Water density** g/ml	**Density** g/ml	**SHC** J/(g K)	**Volume expansion coefficient** 1/K	**VHC** J/(ml K)	**Expansion ratio** ml/J	**Mass-equivalent buoyancy sensitivity at 23 °C** mg/J	**Mass-equivalent buoyancy sensitivity at temperature *T*** mg/J
10	0,999 7	0,965 9	2,073	$7,02 \times 10^{-4}$	2,003	$3,507 \times 10^{-4}$	0,349 6	0,350 5
15	0,999 1	0,962 5	2,088	$7,05 \times 10^{-4}$	2,010	$3,506 \times 10^{-4}$	0,349 6	0,350 1
20	0,998 2	0,959 1	2,103	$7,07 \times 10^{-4}$	2,017	$3,506 \times 10^{-4}$	0,349 5	0,349 7
25	0,997 0	0,955 7	2,119	$7,10 \times 10^{-4}$	2,025	$3,506 \times 10^{-4}$	0,349 5	0,349 3
30	0,995 6	0,952 4	2,134	$7,12 \times 10^{-4}$	2,032	$3,506 \times 10^{-4}$	0,349 5	0,348 9
35	0,993 9	0,949 0	2,149	$7,15 \times 10^{-4}$	2,039	$3,506 \times 10^{-4}$	0,349 5	0,348 4
40	0,992 1	0,945 6	2,164	$7,17 \times 10^{-4}$	2,046	$3,506 \times 10^{-4}$	0,349 6	0,347 8
45	0,990 0	0,942 2	2,179	$7,20 \times 10^{-4}$	2,053	$3,507 \times 10^{-4}$	0,349 6	0,347 3
50	0,987 7	0,938 8	2,194	$7,23 \times 10^{-4}$	2,060	$3,508 \times 10^{-4}$	0,349 7	0,346 7
55	0,985 3	0,935 4	2,209	$7,25 \times 10^{-4}$	2,067	$3,510 \times 10^{-4}$	0,349 9	0,346 0
60	0,982 6	0,932 0	2,224	$7,28 \times 10^{-4}$	2,073	$3,511 \times 10^{-4}$	0,350 0	0,345 3
95 % uncertainty	0,1 %	1,0 %	3,4 %	1,0 %	3,5 %	3,7 %	**average** **0,349 5** **3,7 %**	3,7 %

Density of water and the density and specific heat capacity (SHC) of Acros ® Organics castor oil. Also tabulated for castor oil are properties derived from these: the derived volume expansion coefficient and volumetric heat capacity (VHC), the **expansion ratio** and the mass-equivalent **buoyancy sensitivity** in water at a fixed temperature of 23 °C. The final column shows the **buoyancy sensitivity** in water at the same temperature as the castor oil. The final row shows the uncertainty at a confidence level of approximately 95 %.

---

[1] Acros® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.

D.5 Curve fitting algorithm

At frequencies up to 3 MHz, a linear fit was adequate to determine the weight of the **target** when the power is switched off. From 3 MHz upwards, an exponential function was preferred (Figure D.3) of the form:

$$y = ae^{bx} + c$$

where

y is the apparent mass sequence (mg);

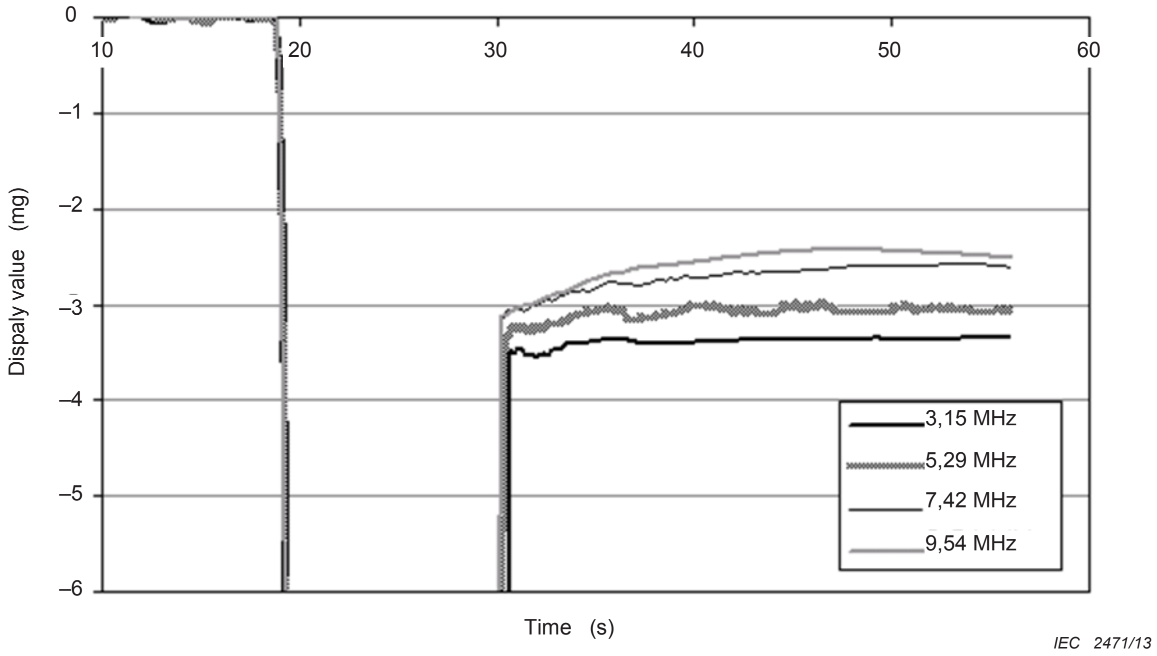
x is the time after the end of insonation (s);

a is the amplitude (mg);

b is the damping coefficient (s^{-1});

c is the offset of the exponential function (mg).

a, b and c are the parameters to be determined. To avoid misleading results for noisy or low power measurements, the exponential fit parameter, b, was constrained to the range 0,07 s^{-1} to 0,125 s^{-1} based on the observed decay curves at the **higher output powers**. The upper and lower bounds for c were arbitrary. During analysis a section of data typically between 15 s and 20 s long, starting a few seconds after the end of insonation was used to fit the exponential function. The fitted exponential function was then used to extrapolate in time to the instant the transducer was switched off and subsequently both the apparent mass and the rate of change of mass of the **target** were determined.



NOTE This graph is inverted compared to Figure D-2 because the transducer was placed below the **target** pointing upwards rather than above and pointing down.

Figure D.3 – Time history of the apparent mass of the castor oil target at different frequencies following an insonation of approximately 1 W acoustic power for a period of 10 s

Table D.2 – Absorption coefficient of castor oil as a function of temperature

Temperature (°C)	**Absorption coefficient for castor oil at 1 MHz** ($\mathrm{dB\ cm^{-1}\ MHz^{-1.7}}$)
10	1,38
20	0,83
30	0,50
40	0,32

D.6 Correction for thermal losses

If the heat flow between the **target** and surrounding water after insonation is significantly different from the heat flow before insonation, it may be necessary to correct for heat flow which occurred during the insonation period. The change in heat flow is most likely due to a progressively increasing temperature in the absorbing liquid but, in principle, it may also be due to changing environmental conditions or it may happen when the temperature of the **target** is initially much higher or lower than the water temperature.

In [7] it is shown that, subject to the assumptions in that paper, the correction in the buoyancy force, dB, can be calculated from the rate of change of weight or displayed mass, M, immediately before and immediately after insonation, and the duration of insonation, t_0:

$$\mathrm{d}B = \frac{t_0}{2}\left[\left.\frac{\mathrm{d}M}{\mathrm{d}t}\right|_{\mathrm{after}} - \left.\frac{\mathrm{d}M}{\mathrm{d}t}\right|_{\mathrm{before}}\right]$$

NOTE An alternative explanation for the shape or form of the variation of weight after the end of insonation observed in [7] is that some or all of the change is due to **acoustic streaming** currents building up during insonation and then decaying. However, this would mean that the correct buoyancy change is close to the simpler linear fit values given in Table 1 of [7] and the analysis method actually used would overestimate the correct power by approximately 20% at 9,151 MHz. Nevertheless, it is possible that streaming currents are having a significant influence on the time variation of the weight of the **target**, which introduces an uncertainty. The use of a streaming foil at frequencies above about 3 MHz will greatly reduce the uncertainty due to possible **acoustic streaming**. Another approach is to direct the transducer horizontally at the entry window of the **expansion target** so that the balance is not sensitive to the horizontal streaming forces.

D.7 Uncertainty

The uncertainty in determining the incident acoustic power is dependent on frequency, power level, transducer geometry and **target** design. As an example, [7] calculates the estimated uncertainty in P_i for a 1 MHz focused bowl transducer of diameter 60 mm and radius of curvature 120 mm; the **target** is 12 cm in diameter and 15 cm long with 5 mm of acoustic absorber close to the rear surface; the distance between the **target** and the transducer face is 30 mm. The **output power** was 50 W and each insonation lasted 10 s, giving an energy output of 500 J per insonation and an anticipated buoyancy change of 170 mg. The overall uncertainty was ± 3,4 %: some sources of uncertainty were also expected to introduce a bias in the final result.

Annex E
(informative)

Influence of attenuation and acoustic streaming on determining incident and output powers

E.1 General

In general, the **incident power** differs from **the output power** due to the effects of **attenuation**, **nonlinear loss** and **streaming** in the water path between the transducer and the **target**. The ratio of **output power** to **incident power** will generally depend at least on distance, frequency and **target** geometry; when nonlinear propagation occurs, the ratio will also depend on drive voltage.

If the aim is to determine the **output power**, the **target** should normally be placed as close as possible to the transducer to minimise these systematic effects and the uncertainty associated with them. This will also help avoid the need to use a streaming foil, which is preferable since it simplifies the experimental arrangement and eliminates a potential source of reflection and transmission loss.

E.2 Linear propagation

E.2.1 General

For a plane wave under conditions of linear propagation, the **incident power**, P_i, decreases logarithmically with distance so that

$$P_\mathrm{i}(z) = P \exp(-2\alpha f^2 z) \tag{E.1}$$

where

P is the **output power**;

z is the distance from the transducer face to the **target** along the beam-axis;

α is the amplitude attenuation coefficient of plane-waves in water;

f is the acoustic frequency.

NOTE Whilst not strictly correct, the relationship in equation E.1 is approximately true, and therefore useful, for other transducers which are not too convergent or divergent and is used in the rest of this clause to illustrate the principle of determining **output power**.

The momentum flux, p, of the wave at distance z is given by

$$p(z) = \frac{P}{c} \exp(-2\alpha f^2 z) \tag{E.2}$$

where

c is the speed of sound in water.

Total momentum is conserved and the momentum lost from the wave by attenuation is converted to momentum of the water in the form of streaming currents set up in the propagation path. Once streaming currents are fully established, the **acoustic streaming** momentum flux, p_str, at distance z is therefore given by

$$p_{\mathrm{str}}(z) = \frac{P}{c}\left(1 - \exp(-2\alpha f^2 z)\right) \tag{E.3}$$

E.2.2 Radiation force method

In a **radiation force** balance, the **incident power** is determined from the change in force on the **target** at the start or end of insonation. This change in force is caused by a combination of the acoustic and streaming momenta intercepted by the **target**. For an ideal absorbing **target**, the acoustic momentum of the intercepted wave is reduced to zero and the intercepted streaming momentum is also reduced, although not generally to zero. The **target** can therefore be considered as having 'recovered' some fraction, L, of the streaming momentum and the total force, F_{tot}, is the sum of the **radiation force**, F, and the streaming force, F_{str}:

$$F_{\mathrm{tot}} = F + F_{\mathrm{str}} = \frac{P}{c}\left[\exp\left(-2\alpha f^2 z\right) + L\left(1 - \exp(-2\alpha f^2 z)\right)\right] \tag{E.4}$$

In principle, it is possible for all of the streaming momentum to be 'recovered' resulting in a total force that is independent of distance but, in practice, a decrease in the force with distance is still observed. In general, L may vary with **target** shape, transducer radius or frequency. Provided $2\alpha f^2 z << 1$, Equation E.4 can be expanded as a Taylor series to give

$$F_{\mathrm{tot}} = F + F_{\mathrm{str}} = \frac{P}{c}\left[1 - (1 - L)(2\alpha f^2 z)\right] \tag{E.5}$$

L can therefore be determined experimentally from measurements of the reduction in total force as a function of z (it is important to check also for variations sub-wavelength scale caused by acoustic reflections).

NOTE For a plane absorbing **target** much larger than the diameter of an collimated circular transducer, L has been determined previously to be in the range 0,6 to 0,8.

There are three approaches to determining the **incident power** and **output power** from the measured total force:

a) Using a **target** for which L is already known, calculate the **output power** from the total force using Equation E.4: the **incident power** can be calculated from equation E.1;

b) Reduce the distance, z, so that $\exp(-2\alpha f^2 z)$ is close to 1.0 and attenuation can be ignored: the **radiation force** is then equal to the total force and the **incident power** can be calculated from equation E.1;

c) Measure F_{tot} as a function of distance, z, so that a value of the force at zero distance (where $\exp(-2\alpha f^2 z)=1$) can be calculated by extrapolation and attenuation can be ignored: the **radiation force** is then equal to the total force extrapolated to zero distance and the **incident power** can be calculated from equation E.1;

d) Reduce L to zero by inserting a streaming foil close to the **target**: the **incident power** can then be determined from the measured **radiation force**, F, and the **output power** from equation E.1.

For a convergent transducer with linear propagation, it is reasonable to adopt the same approach except that a focusing correction still has to be applied. For a diverging transducer, the **target** may also intercept a smaller percentage of the power as the distance increases, so Equation E.4 is not appropriate.

E.2.3 Buoyancy change method

The buoyancy change method does not rely on measurement of momentum changes. The change in the buoyancy force, B, allows the **incident power** to be determined; the **output power** can then be calculated using equation E.1.

However, the existence of the **radiation force** and the streaming force influence the displayed weight of the **target** and therefore makes the determination of B more difficult. The **radiation force** is approximately 20 times larger than the buoyancy change for a 10 s insonation: it stops immediately at the end of insonation although the **target** may continue to oscillate for some time. The size of the streaming force is of the order of the streaming momentum given in equation E.3 and depends on the acoustic frequency and distance: a precise description is not available but it begins to reduce at the end of insonation and may take many seconds to stop completely. This streaming force can be eliminated by the use of a streaming foil.

NOTE The change in displayed weight due to the decay of streaming currents may appear similar to the change due to thermal losses through the entry window of an **expansion target**. Both effects may occur simultaneously but, if streaming currents dominate thermal losses, the correct **buoyancy change** is determined after the streaming currents have died down (for instance 10-20 s after the end of insonation); if thermal losses dominate, however, the correct **buoyancy change** is that immediately after the end of insonation (and even at this point some energy has already been lost). Consequently, in the former limiting case, the displayed weight gets closer to the correct value with time after insonation; whereas, in the latter limit, the displayed weight gets further from the correct value. This supports the interpretation and analysis presented in [7] and indicates that, at least for the low power, collimated transducer studied there, the effect of thermal losses dominates over streaming forces.

E.3 Nonlinear propagation

E.3.1 General

The absorption coefficient of water varies with the square of the frequency, meaning that energy in any harmonics generated by nonlinear propagation will be more strongly absorbed than energy in the fundamental. Consequently, both the energy and momentum of the acoustic wave will decrease more rapidly with distance than for linear propagation. When the ultrasound wave becomes sufficiently nonlinear, it will form an acoustic shock in parts of the beam (typically this occurs on the main focal lobe but it may also form in other locations). When this happens energy is lost from the wave very rapidly and the power reaching a specified distance may decrease by more than 10 % cm^{-1}.

E.3.2 Radiation force method

In the absence of a streaming foil, the majority of the momentum lost from the wave to **acoustic streaming** will be intercepted by the **target** and experienced as a streaming force. However, since the fraction of energy in the harmonics increases with distance in a way which also depends on the acoustic pressure, there is no simple, general way to determine precisely either the **incident power** or the **output power** using the **radiation force** method other than by inserting a streaming foil close to the **target**. Use of a foil permits the **incident power** to be determined; equation E.1 can then be used to estimate the **output power** provided that the distance, z, is small enough that significant energy has not been shifted to the harmonics within the propagation path.

It is preferable therefore to minimise the effects of nonlinear propagation by measuring as close to the transducer as possible. At distances where **nonlinear loss** is not too large, a better estimate of **output power** may be obtained by measuring over small range of distances (for instance between 3 mm and 10 mm) and extrapolating to zero distance. This will also give an estimate of the uncertainty due to **nonlinear loss**.

E.3.3 Buoyancy change method

The buoyancy change method does not rely on measurement of momentum changes. The change in the **buoyancy force**, B, allows the **incident power** to be determined using Equation 3; the **output power** can then be calculated using equation E.1.

The same considerations apply as in E.2.3 except that the streaming forces may be larger in the presence of nonlinear propagation and thermal losses from the entry window will be larger due to more energy being absorbed closer to the window.

Annex F
(informative)

Avoidance of cavitation

F.1 General

Degassing methods for the preparation of water for ultrasound measurements are described in the IEC/TR 62781. For use with HITU systems, degassing under vacuum is preferred.

The gas level required to prevent bubble formation will depend on many factors including **acoustic working frequency** and maximum negative pressure in the water path. The total amount of dissolved gas in the water should preferably be < 2 mg/l during all measurements, and may need to be lower in some cases. Changing or fluctuating **radiation force** may indicate the formation of bubbles. The use of degassed water is recommended at all power levels. Bubbles may form on surfaces in gassy water if the temperature of the water increases. Bubbles formation can also be induced by ultrasound and may also form at power levels below 1 W if the transducer is small enough. Consequently it is recommended to check for the presence of bubbles especially on the transducer and **target** surfaces before, during and after each measurement. Chemical degassing methods which remove only one or a few gas components (e.g. the use of Na_2SO_3) are not generally sufficient for HITU measurements. Provided more general methods of degassing are used, monitoring of the oxygen content is simple to do and provides information about the effectiveness of the degassing and the extent of subsequent regassing. The concentration of dissolved oxygen in degassed water kept in an open tank increases over time.

Annex G
(informative)

Transducer efficiency

G.1 Overview

The determination of **acoustic efficiency** in Clause 8 involves both the measurement of time average **transducer electrical power** and (ultrasonic) **output power**. **Transducer electrical power**, P_{el}, can be found from the measurements of current amplitude, I, flowing into the **ultrasonic transducer**, and the voltage amplitude, U, across the **ultrasonic transducer** and from the phase, ψ, between them by using standard electrical engineering methods such as $P_{\mathrm{el}} = (U I \cos \psi) /2$ or from equivalent time average or r.m.s. values.

This annex describes alternative approaches to considerations of efficiency for **ultrasonic transducers** and **HITU equipment**. It is not a required part of this standard but it may be useful to some users of this standard.

Time-average **electroacoustic efficiency** can be determined from the ratio of time average acoustic **output power**, as measured by means described in the main text of the document, to the time-average power available from electrical source driving the transducer. In the simplest case, for a simple voltage generator operating at a frequency f, power is transmitted to the real part of the transducer impedance. Electrical efficiency can be described in terms of the real power delivered to the real part of the **transducer impedance** divided by the maximum power available from the generator as described in more detail below. This delivered electrical power then is converted into acoustical power travelling out of the transducer in the intended direction of propagation. Determining **electroacoustic efficiency** requires the measurement of time-average acoustic **output power**. The situation may be complicated by an intervening matching network and cable between the source and transducer. A number of special cases will be described as well as measurement methods.

G.2 Terms and definitions

The following defined terms are used in this annex in addition to the terms defined in the normative part of this standard.

G.2.1
radiation efficiency
AE
ratio of acoustic **output power** to the **radiation power**

Note 1 to entry: Radiation efficiency is unitless.

G.2.2
electrical efficiency
EE
ratio of the **radiation power** to the **reference power**

Note 1 to entry: Electrical efficiency is unitless.

G.2.3
electroacoustic efficiency
EA
ratio of acoustic **output power** to the power delivered to the **reference power**. It is also the product of two factors, a time-average electrical efficiency, *EE*, and a time-average radiation efficiency, *AE*

Note 1 to entry: Electroacoustic efficiency is unitless.

G.2.4
radiation impedance

Z_A
acoustical part of **transducer impedance** of an **ultrasonic transducer** of which R_A and X_A are its real and imaginary parts

Note 1 to entry: Radiation impedance is expressed in ohm, Ω.

G.2.5
radiation power

P_RA
time-average power delivered to the **radiation resistance** of the **transducer impedance**

Note 1 to entry: Radiation power is expressed in watt, W.

G.2.6
radiation resistance

R_A
real part of the acoustic **radiation impedance** of an **ultrasonic transducer**

Note 1 to entry: Radiation resistance is expressed in ohm, Ω.

G.2.7
reference power

P_g
maximum time-average power available from the driving source for the **ultrasonic transducer** when the **reference impedance** is complex, Z_g, then the load is the matched conjugate load, Z_g^* and the real part of Z_g is R_g

Note 1 to entry: Reference power is expressed in watt, W.

G.2.8
reference impedance

Z_g
impedance of the source providing the reference power

Note 1 to entry: Reference impedance is expressed in ohm, Ω.

G.2.9
transducer impedance

Z_T
electrical impedance of an **ultrasonic transducer** consisting of a real part (**radiation resistance**) and an imaginary part

Note 1 to entry: Reference impedance is expressed in ohm, Ω.

G.3 Electroacoustic efficiency

Typical transducer measurements are made either as a function of frequency or in the time domain under controlled measurement conditions. A purpose of these measurements is to characterize the response of the device under specified conditions independent of the drive waveforms. Measurements of either the frequency response (or complex spectrum) of the device or its impulse response are taken so that, under linear conditions, the measured response of the device can be used for simulations of other load conditions and drive waveforms under the assumption of linear conditions [15]). In addition, the response of the device can be compared on a consistent basis to similar devices.

Even though these conventional transducer measurement methods can be applied to HITU transducers, it is convenient to use a simpler approach for measurement of **electroacoustic**

efficiency through the use of time-average parameters. **Electroacoustic efficiency** is defined as

$$EAE = P_A / P_g \tag{G.1}$$

where

P_A is the time-average acoustic **output power;**

P_g is the total time average **reference power** available from a source generator.

First, a standard situation under nearly linear conditions is described and later, other cases will be considered.

As shown in Figure G.1a), when a known voltage generator is matched to its source impedance, the total power available from the generator becomes the time average **reference power**,

$$P_g = U_g{}^2 / 8R_g, \tag{G.2}$$

where

U_g is the source voltage;

P_A is the time average **output power**.

Usually the source impedance is real, R_g. When the source impedance is complex, Z_g, then the load is the matched conjugate load, $Z_g{}^*$ and the real part of Z_g is R_g as in Figure G.1a). Note that a standard signal generator can be used as a source for this purpose. More complicated circumstances and sources are described later.

In the normal configuration, the source is connected to a transducer as shown in Figure G.1b). A time-average **electroacoustic efficiency** is also the product of two factors, a time-average **electrical efficiency**, EE, and a time-average **radiation efficiency**, AE,

$$EA = EE \times AE \tag{G.3}$$

$$EA = [P_{RA} / P_g][\, P_A / P_{RA}\,] \tag{G.4}$$

$$EA = P_A / P_g \tag{G.5}$$

The **electrical efficiency**, EE, is therefore the ratio of the time-average **radiation power**, P_{RA}, which is delivered to the real part (**radiation resistance**, R_A) of the **transducer impedance**, Z_T, divided by the average **reference power**, $P_{g.}$ The **radiation efficiency**, AE, is the ratio of the time-average acoustic **output power**, P_A, divided by the time-average **radiation power**, $P_{RA,}$ which is delivered to the real part (**radiation resistance**) of the **transducer impedance**.

G.4 Introduction to measurement of electrical efficiency

Because of acoustic waves generated by the transducer through the piezoelectric effect, the electrical impedance appearing at the transducer terminals is affected by the acoustic loading. To account for this effect, a **radiation impedance**, Z_A, is added to the capacitive reactance of the transducer so that an equivalent circuit for the overall electrical **transducer impedance** is

$$Z_T\ (f) = Z_{\mathrm{A}}\ \mathrm{i}(1/\omega C_0) = R_{\mathrm{A}}\ (f) + \mathrm{i}[\,X_{\mathrm{A}}\ (f) - 1/\omega C_0\,] \qquad \text{(G.6)}$$

Here Z_{A} is **radiation impedance** of which R_{A} and X_{A} are its real and imaginary parts and C_0 is transducer capacitance, and circular frequency is $\omega = 2\pi f$. The transducer impedance can be represented by an equivalent circuit shown in Figure G.2a). This circuit, being just electrical, does not, however, describe the acoustic response; therefore it is not a replacement for a more complete model described later. Transducer **impedance** can be measured by a network analyzer.

To first order, the total time average real electrical power flowing into the transducer for an applied voltage U and current I at a certain frequency f is,

$$P_{\mathrm{E}}(f) = I(f) \times I(f) \times R_{\mathrm{A}}(f)/2 \qquad \text{(G.7)}$$

$$P_{\mathrm{E}}(f) = U(f) \times U(f)\,/\,2R_{\mathrm{A}}(f) \qquad \text{(G.8)}$$

where

I is current flowing through the transducer;

U is the voltage across the radiation resistance.

The simplest configuration is the transducer connected directly to the voltage generator. Figure G.2a) depicts a slightly more complicated case with a tuning network between the source and transducer. In this case the impedance seen to the right of the source is no longer R_{A}. The true **electrical efficiency** can no longer be determined directly because the real power flowing to the right of the source is no longer P_{E} given by Equations G.7 and G.8.

For a more general transmitting configuration, there may be more complicated matching networks and/or cable as depicted in Figure G.2b). Here this more general network is represented by an ABCD matrix ([14] and [15]). Through standard electrical engineering practice, if the network is known, then P_{E} can be determined. If only a measure of **electroacoustic efficiency** is needed, it is not necessary to determine P_{E}.

These methods are based on linear assumptions and standard practice and are therefore transferable and repeatable under different laboratory conditions. Under certain circumstances, the time-average **electroacoustic efficiency** of a transducer connected to a nonlinear HITU source is desired. In this case, the source impedance and voltage delivery may be nonlinear and/or vary with time. Under these circumstances, the methods described here can only be used approximately. The main difficulty is determining an average value for the source impedance for the duration of excitation. If the voltage waveform is nonlinear then the waveform and drive level and source used can be documented sufficiently to allow repeatability of the measurement.

G.5 Introduction to measurement of radiation efficiency

As mentioned earlier, **electroacoustic efficiency** is the product of two factors, an **electrical efficiency**, EE, and a **radiation efficiency**, AE. A typical piezoelectric transducer radiates sound in two directions called “right” and “left”. In addition there may be acoustic absorption and other internal losses that affect the amount of acoustic power radiated from the right (or front) face of the transducer that are included in the acoustical term. The time-average **radiation efficiency** can be rewritten from Equation G.4 as

$$AE = P_{\mathrm{A}}\ /P_{\mathrm{RA}} \qquad \text{(G.9)}$$

where P_A is the time average **output power** delivered from the right or front of the transducer as measured by a **radiation force** balance or other means described in this document and P_{RA} is the radiation power given in the previous clause. This key equation shows that AE is the ratio of the acoustic power to the right divided by the power reaching the radiation resistance. This result is the reason why the real power reaching the transducer impedance must be determined in order to properly calculate the overall electroacoustic efficiency. Figure G.3 illustrates this point as well as the split of the acoustic power between the left and right sides of the transducer.

For an air-backed transducer, under ideal conditions, $AE = 1$, or $P_A = P_{RA}$. However, because of internal losses, matching layers and lenses, AE is less than 1 in practice.

G.6 Measurement of electroacoustic efficiency

The preferred measurement configuration is with the transducer mounted in a **radiation force** balance. This setup provides repeatable acoustic loading of the transducer for electrical measurements as well as acoustic power measurements.

To calculate the **reference power** available from the source generator, the source is loaded with its conjugate matched impedance. For the case of a real source impedance, R_g, measured or known, Equation G.2 can be used directly. Alternatively, the voltage across the matched load can be used in Equation G.2. These methods apply to the excitation selected.

The simplest configuration is the transducer connected directly to a voltage source. The characteristics of the reference signal source are either known or are to be measured. The impedance of the source, Z_g, can be given by the manufacturer or can be measured as a function of frequency by a network analyzer. The voltage U_g can be determined from an open circuit measurement.

In order to determine time average **reference power**, the same source excitation is selected for both electrical and acoustic measurements. If efficiency at one frequency is required, then the source can be set for either continuous wave excitation or a long tone burst, with compensation for duty cycle for the computation of the time average power. For the single frequency case, the time average power is related to the r.m.s. voltage squared so that $U_g = \sqrt{2} \times U_{g,rms}$ in Equation G.2. If the **electroacoustic efficiency** for a range of frequencies is needed, each one can be measured individually. In general, for a waveform excitation, the source is loaded as described in the next step and the waveform across the real part of the matched load is taken and the time average voltage is used in Equation G.2. The **reference power** for waveforms containing a range of frequencies can be determined from

$$P_G = \frac{1}{T\,4\,R_G} \int_{t_1}^{t_2} |\,U_G^2(t)\,|\,\mathrm{d}t = \frac{1}{F\,4\,R_G} \int_{f_1}^{f_2} |\,U_G^2(f)\,|\,\mathrm{d}f \qquad \text{(G.10)}$$

In which $T = t_2 - t_1$, the end and beginning times of the waveform and $F = f_2 - f_1$ are the frequencies bounding the spectrum of the waveform.

The time average acoustic **output power** is measured by a **radiation force** balance or comparable method described in the main text for the same excitation. Then the **electroacoustic efficiency** is calculated from Equation G.5,

$$EA = P_A / P_g$$

G.7 Measurement of electrical efficiency and radiation efficiency

Both of these measurements are dependent on the determination of radiation power, or the real power delivered to the real part of the transducer impedance, P_{RA}, as given by Equation G.4. Because radiation resistance is measured as a function of frequency, this radiation power is also most conveniently determined as a function of frequency as expressed by Equation G.8 where $U(f)$ is the voltage across the radiation resistance. Because only the voltage, U_{T}, across the entire transducer can be accessed,

$$P_{\mathrm{E}}(f)=\frac{R_{\mathrm{A}}}{2}\frac{|U_{\mathrm{T}}|^{2}}{|Z_{\mathrm{T}}+Z_{\mathrm{g}}|^{2}} \tag{G.11}$$

The above equation can be used for a single frequency excitation. In general, the time average value of radiation power can be found as

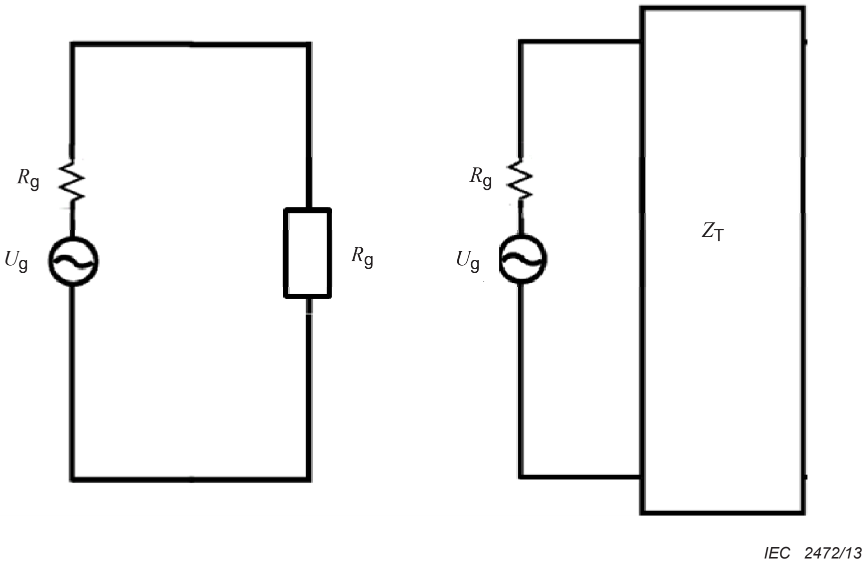
$$P_{\mathrm{RA}}=\frac{2}{T}\int_{t_1}^{t_2}|P_{\mathrm{E}}(t)|\,\mathrm{d}t=\frac{2}{F}\int_{f_1}^{f_2}|P_{\mathrm{E}}(f)|\,\mathrm{d}f \tag{G.12}$$

For cases in which the source is not directly connected to the transducer, the intervening network must be characterized to infer the power in the radiation resistance as described earlier through standard electrical engineering methods. For example, from an ABCD matrix approach and a source impedance, R_{g}, at each frequency

$$EE=\frac{4R_{\mathrm{A}}R_{\mathrm{g}}}{\left|A_{\mathrm{ET}}\left(Z_{\mathrm{T}}+R_{\mathrm{g}}\right)+B_{\mathrm{ET}}\right|^{2}} \tag{G.13}$$

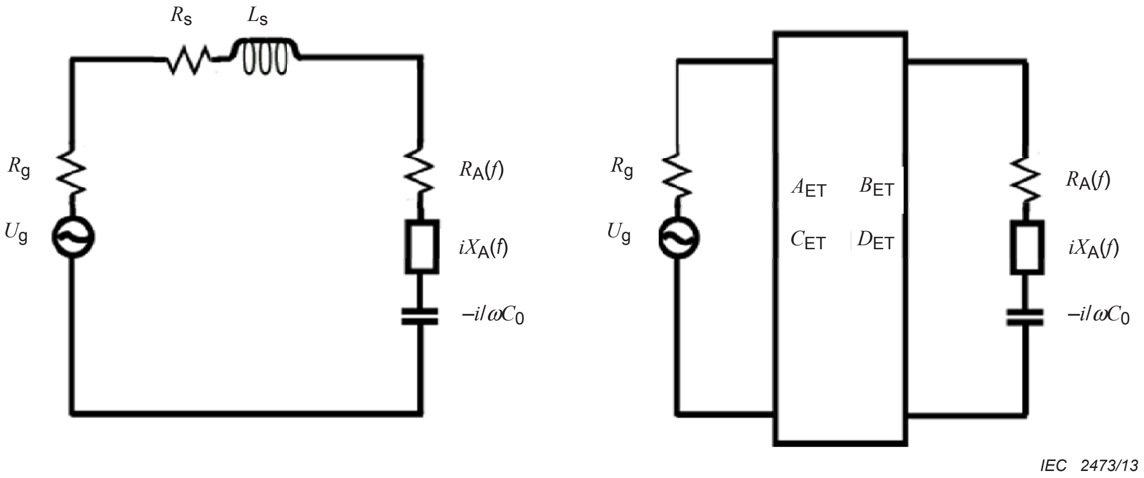
For the example of the tuning inductor in Figure G.3a),

$$EE=\frac{4R_{\mathrm{A}}R_{\mathrm{g}}}{\left(R_{\mathrm{A}}+R_{\mathrm{g}}+R_{\mathrm{s}}\right)^{2}+\left(X_{\mathrm{A}}-\dfrac{1}{\omega\,C_{0}}+\omega\,L_{s}\right)^{2}} \tag{G.14}$$



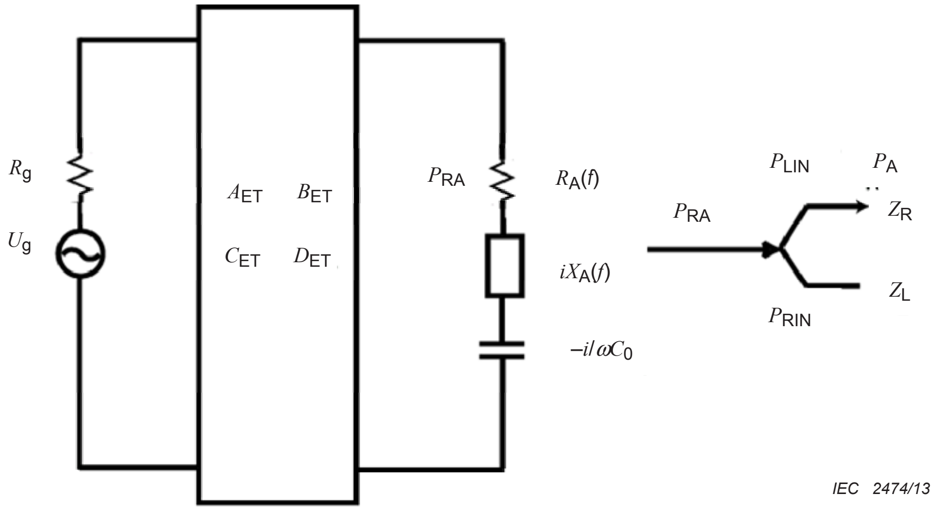
Left: Source generator loaded with a conjugate load. Right: Source generator loaded with a transducer

Figure G.1 – Electrical voltage source under different loading conditions



Left: Simple series inductor and resistor. Right: ABCD representation of a more general network. The elements of the matrix are A_{ET}, B_{ET}, C_{ET}, and D_{ET}.

Figure G.2 – Electrical voltage source and electrical matching network and transducer equivalent circuit



Electrical loss in this diagram is defined as the power reaching the radiation resistance divided by source power and acoustical loss defined as the power reaching the right acoustic load, $P_A = P_{RIN}$, divided by the power reaching the radiation resistance, P_{RA}.

Figure G.3 – Diagram illustrating electrical loss.

Bibliography

[1] O'BRIEN, W.D. Ultrasonic dosimetry, in: *Ultrasound: Its Application in Medicine and Biology,* Editor Fry, F.J., Elsevier Scientific Publishing Company, 1978, pp. 343-397

[2] STEWART, H.F. Ultrasonic measuring techniques, in: *Fundamental and Applied Aspects of Nonionizing Radiation,* Editors Michaelson, S.M., et al., Plenum Press, New York, 1975, pp. 59-89

[3] ZIENIUK, J., and CHIVERS, R.C. Measurement of ultrasonic exposure with radiation force and thermal methods. *Ultrasonics* 14, 1976, pp. 161-172

[4] IEC/TR 62649:2010 *Requirements for measurement standards for high intensity therapeutic ultrasound (HITU) devices*

[5] ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

[6] SHAW, A. A buoyancy method for the measurement of total ultrasound power generated by HIFU transducers*. Ultrasound in Med. & Biol*., Vol. 34, No. 8, 2008, pp. 1327–1342

[7] RAJAGOPAL, S and SHAW, *A.* Buoyancy method – a potential new primary ultrasound power standard*. Metrologia*, 2012, Vol. 49, pp 327–339

[8] IEC/TS 62556[2], *Surgical systems – Specification and measurement of field parameters for high intensity therapeutic ultrasound (HITU) transducers and systems*

[9] IEC 62127-2, *Ultrasonics – Hydrophones – Part 2: Calibration for ultrasonic fields up to 40 MHz*

[10] BEISSNER, K. Minimum target size in radiation force measurements*. J. Acoust. Soc. Am.*76, pp., 1984, pp. 1505-15010

[11] BEISSNER, K. Minimum radiation force target size for power measurements in focused ultrasonic fields with circular symmetry*. J. Acoust. Soc. Am*., 2010, 128, pp. 3355-3362

[12] SHOU, Wende, HUANG, Xiaowei, DUAN, Shimei, XIA, Rongmin, SHI, Zhonglong, GENG, Xiaoming, LI*,* Faqi. Acoustic power measurement of high intensity focused ultrasound in medicine based on radiation force*. Ultrasonics,* 2006, 44, e17–e20

[13] MARUVADA, Subha, HARRIS, Gerald R., HERMAN, Bruce A. and King, Randy L. Acoustic power calibration of high-intensity focused ultrasound transducers using a radiation force technique*. J. Acoust. Soc. Am.*, 2007, 121 (3), pp1434-1439

[14] SITTIG, E. K. Transmission parameters of thickness-driven piezoelectric transducers arranged in multilayer configurations. *IEEE Trans Sonics Ultrasonics,* 1967, SU-14:pp.167-174

[15] SZABO, T. L. *Diagnostic Ultrasound Imaging: Inside Out.* Elsevier Science, August 2004

[16] SZABO, T. L., KARBEYAZ, B. U., Cleveland, R. O. and Miller, E. L. Determining the pulse-echo electromechanical characteristic of a transducer using flat-plates and point targets*. J. Acoust. Soc. Am*., July 2004, 116:90-96

---

[2] To be published

[17] IEC 60050 (all parts), *International electrotechnical Vocabulary* (available at <http://www.electropedia.org>).

[18] IEC 60601-2-62:— [3], *Medical electrical equipment – Part 2-62: Particular requirements for basic safety and essential performance of high intensity therapeutic ultrasound (HITU) equipment*

---

[3] To be published

This page deliberately left blank

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Copyright

All the data, software and documentation set out in all British Standards and other BSI publications are the property of and copyrighted by BSI, or some person or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use. Except as permitted under the Copyright, Designs and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI. Details and advice can be obtained from the Copyright & Licensing Department.

Useful Contacts:

Customer Services
Tel: +44 845 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 845 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

bsi.

...making excellence a habit.™