BS EN 61161:2013

BSI Standards Publication

Ultrasonics — Power measurement — Radiation force balances and performance requirements

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National foreword

This British Standard is the UK implementation of EN 61161:2013. It is identical to IEC 61161:2013. It supersedes BS EN 61161:2007, which will be withdrawn on 6 March 2016.

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.

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English version

Ultrasonics - Power measurement - Radiation force balances and performance requirements
(IEC 61161:2013)

Ultrasons - Mesurage de puissance -
Balances de forces de rayonnement
et exigences de fonctionnement
(CEI 61161:2013)

Ultraschall - Leistungsmessung -
Schallfeldkraft-Waagen
und Anforderungen an ihre
Funktionseigenschaften
(IEC 61161:2013)

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

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Foreword

The text of document 87/520/FDIS, future edition 3 of IEC 61161, prepared by IEC/TC 87 "Ultrasonics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61161:2013.

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)	2013-12-06
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-03-06

This document supersedes EN 61161:2007.

EN 61161:2013 includes the following significant technical changes with respect to EN 61161:2007:

- whereas the second edition tacitly dealt with circular transducers only, the present edition as far as possible deals with both circular and rectangular transducers, Including a number of symbols for rectangular transducers;
- attention is paid to focused cases and the influence of scanning has been added;
- the method of calibrating the radiation force balance now depends on whether the set-up is used as a primary or as secondary measurement tool;
- Annex B (basic formulae) has been updated and in Annex C the buoyancy change method is mentioned (see also future EN 62555).

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 61161:2013 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 60601-2-5	NOTE	Harmonised as EN 60601-2-5.
IEC 61157	NOTE	Harmonised as EN 61157.
IEC 61846:1998	NOTE	Harmonised as EN 61846:1998 (not modified).
IEC 62127-1	NOTE	Harmonised as EN 62127-1.
IEC 62127-2	NOTE	Harmonised as EN 62127-2.
IEC 62127-3	NOTE	Harmonised as EN 62127-3.
IEC 62555 [1)]	NOTE	Harmonised as EN 62555 [1)].

[1)] At draft stage.

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 61689	-	Ultrasonics - Physiotherapy systems - Field specifications and methods of measurement in the frequency range 0,5 MHz to 5 MHz	EN 61689	-

CONTENTS

INTRODUCTION

A number of measuring methods exist for the determination of the total emitted power of ultrasonic transducers ([1], [2], [3][1], see also Annex C). The purpose of this International Standard is to establish standard methods of measurement of ultrasonic power in liquids in the lower megahertz frequency range based on the measurement of the radiation force using a gravimetric balance. The great advantage of radiation force measurements is that a value for the total radiated power is obtained without the need to integrate field data over the cross-section of the radiated sound beam. 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.

Basic safety requirements for ultrasonic physiotherapy devices are identified in IEC 60601-2-5 and make reference to IEC 61689, which specifies the need for acoustic power measurements with an uncertainty better than ± 15 % at a level of confidence of 95 %. Considering the usual degradation of accuracy in the practical application of this standard, reference measurement methods need to be established with uncertainties better than ± 7 %. Ultrasonic diagnostic device declaration requirements including acoustic power are specified in other IEC standards, as for example in IEC 61157.

The measurement of acoustic power accurately and repeatably using a radiation force balance as defined in this standard is influenced by a number of practical problems. As a guide to the user, additional information is provided in Annex A using the same section and clause numbering as the main body.

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[1] Numbers in square brackets refer to the Bibliography.

ULTRASONICS – POWER MEASUREMENT – RADIATION FORCE BALANCES AND PERFORMANCE REQUIREMENTS

1 Scope

This International Standard

- specifies a method of determining the total emitted acoustic power of ultrasonic transducers based on the use of a radiation force balance;
- establishes general principles for the use of radiation force balances in which an obstacle (target) intercepts the sound field to be measured;
- establishes limitations of the radiation force method related to cavitation and temperature rise;
- establishes quantitative limitations of the radiation force method in relation to diverging and focused beams;
- provides information on estimating the acoustic power for diverging and focused beams using the radiation force method;
- provides information on assessment of overall measurement uncertainties.

This International Standard is applicable to:

- the measurement of ultrasonic power up to 1 W based on the use of a radiation force balance in the frequency range from 0,5 MHz to 25 MHz;
- the measurement of ultrasonic power up to 20 W based on the use of a radiation force balance in the frequency range 0,75 MHz to 5 MHz;
- the measurement of total ultrasonic power in well-collimated, diverging and focused ultrasonic fields;
- the use of radiation force balances of the gravimetric type or force feedback type.

(See also Clause A.1)

NOTE 1 A focused beam is converging in the pre-focal range and diverging beyond focus.

NOTE 2 Ultrasonic power measurement in the high intensity therapeutic ultrasound (HITU) range, i.e. beyond 1 W or 20 W, respectively, is dealt with in the future IEC 62555.

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 61689, *Ultrasonics – Physiotherapy systems – Field specifications and methods of measurement in the frequency range 0,5 MHz to 5 MHz*

3 Terms and definitions

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

3.1
acoustic streaming
bulk fluid motion initiated by a sound field

3.2
free field
sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on the sound waves

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

3.3
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).

3.4
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**; or, 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, or within a single attenuating medium

Note 1 to entry: **Radiation force, acoustic radiation force**, is expressed in newton (N).

3.5
radiation pressure
acoustic radiation pressure
radiation force per unit area

Note 1 to entry: This term is widely used in the literature. However, strictly speaking, the **radiation force** per unit area is a tensor quantity [4] and it should be referred to as the acoustic radiation stress tensor when a strict scientific terminology is to be used. The integral quantity "**acoustic radiation force**" is generally preferred in this International Standard. Whenever at some places, the term "**acoustic radiation pressure**" appears it is to be understood as the negative value of the normal radiation stress in the direction of the field axis.

Note 2 to entry: **Radiation pressure, acoustic radiation pressure,** is expressed in pascal (Pa).

3.6
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**

3.7
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

3.8
radiation conductance
G
ratio of the acoustic **output power** and the squared RMS transducer input voltage

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

Note 2 to entry: **Radiation conductance** is expressed in siemens (S).

4 List of symbols

a	radius of a circular ultrasonic source transducer
b_x and b_y	half-dimensions of a rectangular ultrasonic source transducer in x and y direction, respectively (so that 2 b_x and 2 b_y are the transducer's side lengths)
c	speed of sound (usually in water)
d_x and d_y	geometrical focal lengths of a focusing **ultrasonic transducer** in the x-z and the y-z plane, respectively
d	geometrical focal length of a focusing **ultrasonic transducer** in the case of $d_x = d_y = d$
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, $h_d = (b_x^2 + b_y^2)^{1/2}$
h_h	harmonic mean of b_x and b_y, $h_h = 2 / (1/b_x + 1/b_y)$
k	circular wavenumber, $k = 2\pi / \lambda$
P	**output power** of an **ultrasonic transducer**
s	normalized distance from a circular **ultrasonic transducer**, $s = z \lambda / a^2$
z	distance between an **ultrasonic transducer** and a **target**
α	amplitude attenuation coefficient of plane waves in a medium (usually water)
β_x and β_y	focus (half-)angles of a rectangular focusing **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 focusing **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
θ	angle between the direction of the incident ultrasonic wave and the normal to a reflecting surface of a **target**
λ	ultrasonic wavelength in the sound-propagating medium (usually water)
ρ	(mass) density of the sound-propagating medium (usually water)

NOTE 1 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.

NOTE 2 Strictly speaking, in the case of a focusing transducer, the focusing details and the transducer shape are independent of each other, i.e. a circular transducer, too, can have two different focus (half-)angles. With regard to ultrasound practice, however, this standard restricts to the two cases of a circular transducer with one focus (half-) angle and of a rectangular transducer with two focus (half-)angles (which can, of course, be equal to each other).

5 Requirements for radiation force balances

5.1 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 ultrasonic power shall be determined from the difference between the force measured with and without ultrasonic radiation. Guidance is contained in Annex B. Calibration can be carried out by means of small precision weights of known mass.

NOTE Different possible **radiation force** measurement set-ups are presented in Figures F.1 to F.7. Each measurement set-up has its own merits, which are also summarized in Annex F.

5.2 Target type

5.2.1 General

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.5.2.1)

If the **target** is chosen so as to closely approach one of the two extreme cases, i.e. perfect absorber or perfect reflector, the appropriate formula of Annex B shall be used depending on the field structure and the following requirements apply:

5.2.2 Absorbing target

An absorbing **target** (see Figures 1, F.1a, F.3, F.4, F.5a and F.7) shall have

- an amplitude reflection factor of less than 3,5 %;
- an acoustic energy absorption within the **target** of at least 99 %.

(See also A.5.2.2)

5.2.3 Reflecting target

A reflecting **target** (see Figures F.1b, F.2, F.5b and F.6) shall have

- an amplitude reflection factor of greater than 99 %.

A conical reflecting **target** should not be used for power measurements of non-focusing transducers where < 30. A convex-conical reflector with a cone half-angle of 45° shall not be used for power measurements of transducers where $ka < 17,4$, which follows from theoretical consideration of the effects of beam divergence. (See also A.5.3)

NOTE 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.

In addition, a convex-conical reflector with a cone half-angle of 45° should not be used for power measurements of focusing transducers where $d < 32a$. If the geometrical focal length d is not known then a convex-conical reflector with a cone half-angle of 45° should not be used when the distance z_f of the pressure maximum from the transducer is

$$z_f < 1 / [(1/32a) + (\lambda / a^2)]$$

This condition recommends restricting the use of convex-conical reflectors to the unfocused case or the case of weak focusing. If, nevertheless, a convex-conical reflector is used in strongly focused fields and Formula (B.6) is applied, additional uncertainties that are not covered by Clause 7 need to be taken into account. In case of an oblique beam (scanning) conical reflectors should not be used.

The above statements apply to circular transducers. In case of a rectangular transducer, consider all the above conditions twice, replacing a with b_x as well as with b_y, and use the reflecting **target** only if all conditions are fulfilled in a positive sense for b_x as well as for b_y.

(See also A.5.2.3 and Clause B.6)

5.3 Target diameter

The lateral size of the **target** shall be large enough to intercept all significant parts of the field, in the sense that the **radiation force** is at least 98 % of the reference **radiation force**, i.e. that experienced by a **target** of infinite lateral size.

As the reference **radiation force** is often unknown in practice, an alternative requirement for unfocused fields is as follows. The **target** dimension in any lateral direction shall in no case be lower than 1,5 times the corresponding dimension (e.g. the diameter) of the **ultrasonic transducer**.

Whether or not the **target** dimensions should be more than 1,5 times the transducer dimensions, depends on the dimensions of the field cross-section at the particular location of the **target**. The beam dimensions shall be measured or calculated from theoretical estimation as given, for example in A.5.3.

In case of an oblique beam (scanning), i.e. when the beam axis is tilted by a certain angle from the axis of the **radiation force** balance, a larger **target** size is required. In this case, the field cross-section at the particular location of the **target** is not centred to the **target** centre but is shifted from it by a certain amount depending on the tilt angle and the **target** distance, and the required **target** size needs to be increased by this amount.

5.4 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 Vertical beam orientation allows traceability to national mass standards (calibrated weights). Set-ups with horizontal beam orientation exist in practice using either a reflecting **target** [5, 6] or an absorbing **target** [7]. Calibration 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)

5.5 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 1 % of the overall measured power. (See also A.5.5)

5.6 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 to less than 1 % of the overall measured power. (See also A.5.6)

5.7 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 1 %.

5.8 Anti-streaming foils

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** [8]. Its transmission coefficient shall be known from measurement and a correction shall be applied if its influence is more than 1 % of the overall measured power. (See also A.5.8)

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

5.9 Transducer coupling

The **ultrasonic transducer** shall be coupled to the measurement device such that the impact on the overall measured power is less than 1 %, otherwise a correction shall be applied. (See also A.5.9)

5.10 Calibration

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

Further, in case of a non-primary measurement set-up, the **radiation force** balance shall be calibrated by use of an ultrasonic source or sources of known **output power** traceable to a primary measurement standard. The calibration shall be carried out at multiple **acoustic working frequencies** and **output power** levels representative of the range over which the balance is to be used. In this case, the calibration shall be undertaken once every two years or more frequently if there is any indication that the balance sensitivity to ultrasonic power has changed. (See also A.5.10)

NOTE In this standard, “a primary measurement set-up” means a measurement set-up that has taken part in an international key comparison or another international comparison, organized by the CIPM/BIPM.

Depending on the set-up used, corrections for diffraction, focusing angles, energy missing the **target** or not-absorbed/not-reflected by the **target**, absorption in the water path between transducer and **target**, streaming, etc. should be applied as necessary to meet accuracy goals.

6 Requirements for measuring conditions

6.1 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 1 %. (See also A.6.1)

6.2 Transducer/target separation

The distance between the **ultrasonic transducer** surface and the **target**, or foil (if used) and **target**, should be as small as possible in view of the fact that **acoustic streaming** may occur due to the ultrasonic absorption along the sound path. (See also A.6.2)

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 1 %. (See also A.6.2)

6.3 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/TR 62781, referred to in Annex D. Where degassed water is required, the amount of dissolved oxygen in the water shall be < 4 mg/l during all measurements and shall, in addition, be low enough to prevent the occurrence of cavitation. The measurements shall be discarded if any cavitation bubbles are observed. (See also A.6.3)

6.4 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. (See also A.6.4)

6.5 Environmental conditions

For measurements in the milliwatt and microwatt region, 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 1 % effect on the overall measured power.

The measuring device shall be protected against environmental vibrations and air flow. (See also A.6.5)

6.6 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.** (See also A.6.6)

7 Measurement uncertainty

7.1 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 BIPM JCGM 100:2008 [9].

7.2 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 **radiation force** measurements, 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 judgment of the long-term stability of the balance calibration factor. (See also A.7.2)

7.3 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 7.2 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 2. 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 forces** of various magnitudes. In this case, the input quantity at the abscissa of Figure 2 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 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**. 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.

7.5 Target imperfections

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

7.6 Reflecting target geometry

The influence of the reflecting **target** geometry shall be estimated and incorporated into the overall system uncertainty. (See A.7.6).

7.7 Lateral absorbers in the case of reflecting target measurements

The imperfections of the lateral absorbers in the arrangement of Figures F.1b, F.2, F.5b and F.6 shall be estimated and incorporated into the overall system uncertainty. (See also A.7.7)

7.8 Target misalignment

The influence of **target** misalignment shall be estimated and incorporated into the overall system uncertainty. (See A.7.8)

7.9 Ultrasonic transducer misalignment

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

7.10 Water temperature

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

7.11 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)

7.12 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.

7.13 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)

7.14 Plane-wave assumption

The uncertainty contribution due to the use of a plane-wave assumption shall be determined and included in the overall system uncertainty. (See A.7.14)

7.15 Scanning influence

Provisions for power measurements with an absorbing **target** for transducers operating in scanning modes are given in Clause B.7. This involves assumptions on the constancy of the beam parameters during scanning and knowledge of the scan angles. The uncertainty contribution associated with the degree to which the assumptions are fulfilled and with the knowledge of the scan angles shall be determined and included in the overall system uncertainty. The use of reflecting targets is not recommended because of their sensitivity to angle of incidence.

7.16 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)

7.17 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)

7.18 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)

7.19 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.

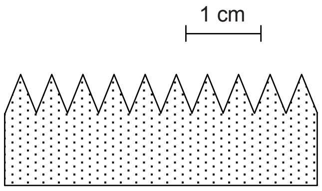
(See A.7.19)

7.20 Acceleration due to gravity

The uncertainty in the acceleration due to gravity, g, is usually rather small in comparison with other uncertainties. The numerical value of g depends on the location of the **radiation force** balance and also on its altitude.

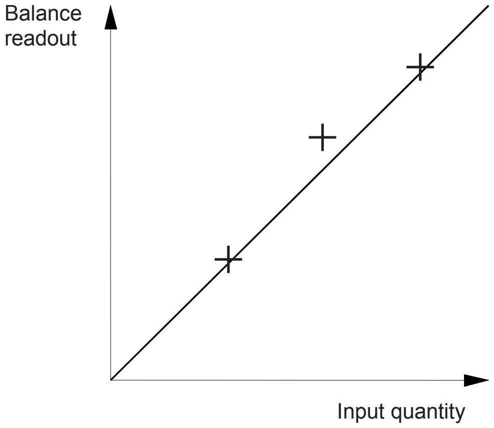
7.21 Other sources

Checks should be performed periodically to determine whether the overall uncertainty as specified in 7.2 to 7.20 using the above guidelines is not influenced by any other sources. (See also A.7.21)



IEC 189/13

Figure 1 – Section through an absorbing target



IEC 190/13

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

Annex A
(informative)

Additional information on various aspects of radiation force measurements

NOTE This annex contains additional information on the specifications of this standard to aid in the actual practical measurement of ultrasonic power. The clause and subclause numbers follow the format of the main body.

A.1 Scope

The **radiation force** is equal to the change in the time-averaged momentum flow [4] and is thus related to ultrasonic intensity and power.

The relationship also depends on the details of the acoustic field and the **target**.

A.2 Normative references

Void.

A.3 Definitions

Void.

A.4 List of symbols

Void.

A.5 Radiation force balances

A.5.1 General

Void.

A.5.2 Target type

A.5.2.1 General

Usually, the aim is to approach most closely one of the two extreme cases: perfect absorber or perfect reflector [10]. The compressibility should be as low as possible to avoid buoyancy changes due to variations of the ambient pressure. Care should be taken in other respects to maximize the stability of buoyancy of the **target**.

To perform power measurements within predictable uncertainty the choice of the **target** type depends on the way the ultrasonic beam deviates from the theoretical plane wave approach. In particular the use of a reflecting **target** may result in unacceptable uncertainties. (See 5.2.3)

A.5.2.2 Absorbing target

Samples of appropriate elastic rubber material with or without wedges are normally used as absorbing **targets**. To increase the absorbing properties, the material may contain inhomogeneities.

Figure 1 shows an example of a set-up of a wedge-type absorber. In this case, the concentration of the inhomogeneities increases from zero at the wedges to 30 % by volume at the rear surface. In this example, hollow glass spheres of diameter of the order of one-tenth millimetre behave satisfactorily as inhomogeneities, since they have only little influence on the density and compressibility of the elastic rubber material.

Other types of absorbers are described in [11,12].

Ultrasonic beams transmitting powers above 10 W or exhibiting high local power densities have been shown to cause very high local temperature rises in the absorber which might lead to damage and changes in its acoustic properties. Temperature rises higher than 50 °C have been observed.

A.5.2.3 Reflecting target

The main problem is to reduce the compressibility of a reflecting **target** because air pressure fluctuations modulate the volume, and thereby the buoyancy, of the **target**, proportional to its compressibility. Plane sound reflectors that are realized by means of air-backed thin metal plates should not be used. Using solid metal plates as reflectors, that are adjusted under an angle of 45° to the sound beam axis, may cause errors [13] due to significant and frequency-dependent transmission through the plate.

Cone-shaped reflectors made of thick-walled hollow bodies or of air-backed thin metal plates are suitable. Cone-shaped reflectors made of very stiff plastic foam, and which are coated with a very thin metal layer produced by electroplating, have proved to be adequate **targets** [10].

– Reflecting **target** – convex

A conical reflector of the convex type is shown in Figures F.1b, F.2 and F.6. The cone half-angle is typically chosen to be 45° so that the reflected wave leaves at right angles to the ultrasound beam axis.

– Reflecting **target** – concave

A conical reflector of the concave type is shown in Figure F.5b. The cone half-angle is typically chosen to be of the order of 60° to 65°, so that the reflected wave is directed nearer to the **ultrasonic transducer** than with the convex-type reflector.

A.5.3 Target diameter

A.5.3.1 Circular piston transducer

In the following, an assessment Formula [14] is given for the minimum value of the **target** radius r 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 %). 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 is:

$$r = a\,[1/(1 + 0{,}53\ \tau_1 s) + \tau_1 s] \tag{A.1}$$

with

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

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

$$\tau_0 = k\ a\ /\ [2\ \pi\ (\eta^2 - 1)^{1/2}]$$

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

where

z is the distance between the **ultrasonic transducer** and the **target**;

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 **ultrasonic transducer** and the **target**.

NOTE The choice of some symbols has been modified here in comparison with earlier editions.

Equation (A.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 r. The influence of absorption and **acoustic streaming** is considered separately.

By way of precaution and in accordance with 5.3, r should never be reduced below 1,5 a, 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. r 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.

In the case of a 45° convex-conical reflector there is a certain limiting ka value of the transducer below which the requirements of these formulae can never be fulfilled, irrespective of the reflector size and even if the reflector apex is as close as possible, namely in contact with the transducer surface. This limiting value is $ka = 17{,}4$.

A.5.3.2 Rectangular piston transducer

Equation (A.1) can be extended to the case of a rectangular piston transducer as follows. This applies to a circular absorbing **target** with radius r. The formula again gives a minimum **target** radius so that the **radiation force** is at least 98 % of the **radiation force** that would exist if the **target** were of infinite cross-sectional size.

$$r = h_\mathrm{d} / (1 + \mu\,\tau_1\,s) + h_\mathrm{h}\,\tau_1\,s \qquad \text{(A.2)}$$

with

$$\mu = 0{,}53\,h_\mathrm{h} / h_\mathrm{d}$$

$$\eta = 0{,}98 + 0{,}01\,\pi\,kh_\mathrm{h}$$

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

$$\tau_0 = kh_\mathrm{h} / [2\pi(\eta^2 - 1)^{1/2}]$$

$$\Delta\tau = \begin{cases} 0{,}7 & \text{if } kh_\mathrm{h} \le 9{,}3 \\ 6{,}51 / kh_\mathrm{h} & \text{if } 9{,}3 \le kh_\mathrm{h} \le 43{,}4 \\ 0{,}15 & \text{if } 43{,}4 \le kh_\mathrm{h} \end{cases}$$

where

$s = z\,\lambda / h_\mathrm{h}^2$	is a formal expression here that is not necessarily associated with the near-field length;
$h_\mathrm{h} = 2 / (1/b_\mathrm{x} + 1/b_\mathrm{y})$	is the harmonic mean of the transducer half-dimensions;
$h_\mathrm{d} = (b_\mathrm{x}^2 + b_\mathrm{y}^2)^{1/2}$	is the transducer half-diagonal.

By way of precaution and in accordance with 5.3, r should never be reduced below 1,5 h_d, even if this were possible in accordance with the above equation.

A.5.3.3 Circular focusing transducer

In this case, the assessment procedure (taken from [15]) for the minimum value of the radius r of an absorbing circular **target** is different from that in A.5.3.1. 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. The quantities a, d, k, z and γ explained in Clause 4 are involved; d and z are understood here as being counted from the plane defined by the rim of the active part of the transducer.

NOTE 1 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:

$$r/a = 1 \quad \text{for} \quad z/d = 0 \tag{A.3}$$

$$r/a = 0{,}5 + 6{,}24 \times (ka \sin\gamma)^{-0{,}885} \quad \text{for} \quad z/d = 0{,}5 \tag{A.4}$$

$$r/a = 12{,}54 \times (ka \sin\gamma)^{-0{,}749} \quad \text{for} \quad z/d = 1 \tag{A.5}$$

$$r/a = 1 + 29{,}1 \times (ka \sin\gamma)^{-0{,}892} \quad \text{for} \quad z/d = 2 \tag{A.6}$$

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 2 The above assessment is a worst-case consideration for uniform and apodizing amplitude distributions and it does not apply when the transducer has a central hole.

A.5.4 Balance/force measuring system

The type of balance needed depends strongly on the magnitude of the ultrasonic power to be measured. A power value of 10 mW is equivalent to a **radiation force** (in water on an absorbing **target**) of 6,7 μN corresponding to a mass equivalent of 0,68 mg, whereas a power value of 10 W means a **radiation force** of 6,7 mN corresponding to a mass equivalent of 0,68 g. In the former case, an electronic, self-compensating microbalance is the most suitable instrument, whereas in the latter case, an appropriate electronic balance or a purely mechanical laboratory balance [16] may be used. In any case, compensation of the **target** displacement at the position of rest is essential.

If the balance/force measuring device is calibrated by means of small weights of known mass or if, for other reasons, the readout of the balance/force-measuring device is given in mass units, the measurement result in mass units is to be multiplied by the acceleration due to gravity, g, to convert it into a force. If the measurement result is given in milligrams (or grams), multiplication by g yields a force in micronewtons (or in millinewtons, respectively). When the force is converted to ultrasonic power in accordance with the formulae given in Annex B, the use of a speed of sound value in metres per second, as for example c = 1 491 m × s^{-1} in pure water at 23°C, then yields a power in microwatts (or in milliwatts, respectively).

The numerical value of g depends on the location of the **radiation force** balance. The appropriate value must be used which is, for example, g = 9,81 m × s^{-2} in central Europe, but it also depends on the altitude.

A.5.5 System tank

It is necessary to ensure that neither the **target** nor any other parts of the measuring device give rise to any substantial ultrasonic reflections, or that the reflections are emitted in such directions that they do not return to the **ultrasonic transducer** and react on it. Otherwise, the measured power will not in general be equal to the desired **free-field** value.

If a reflecting **target** is used, reflections from the tank walls are critical. Their influence on the measured power depends on the geometry of the tank. If the tank is circular in cross-section, all reflections may return to the **target** (and via the reflecting **target** to the transducer). In this case the 1 % requirement of 5.5 leads to a requirement of again ≤ 1 % energy reflectivity of the tank wall including lining.

In case the system tank is directly placed on the balance pan (see measurement set-up in Figure F.4), care should be taken to centre the tank correctly on the pan.

A.5.6 Target support structures

If the **target** is suspended by wires which penetrate the liquid surface then they should have a diameter as small as possible to reduce measurement errors that may be caused by incomplete wetting of the wire or by dust particles. The use of a small wire diameter is even more important in a situation where the **ultrasonic transducer** is placed above the **target** (radiation downwards) and where several suspension wires may be needed, as in Figure F.5.

NOTE 1 Platinum-iridium wire of diameter 60 μm or 80 μm is suitable.

NOTE 2 The influence of the suspension wire(s) can be checked by calibrating the system using weights of known mass and with the **target** suspended in water, in accordance with 7.2 and A.7.2.

Special notice has to be given when the set-up presented in Figure F.4 is used. Here the transducer outer surface will contribute to disturbing surface tension forces. Some delay to start a measurement should be allowed to stabilize the water level.

A.5.7 Transducer positioning

Void.

A.5.8 Anti-streaming foils

Two types of streaming can be relevant: the heat convection type, as for example in the case of an **ultrasonic transducer** warm-up during ultrasonic operation, and the **acoustic streaming** which is associated with ultrasonic attenuation and, hence, occurs primarily in the high-frequency range.

Acoustic streaming may occur when there is significant ultrasonic absorption along the sound path (long sound path and/or high frequency [17]). Its effect can be compensated by (a) correcting the **radiation force** result, (b) using an anti-streaming foil or (c) varying the **target** distance and extrapolating the **radiation force** result to zero distance.

If a foil is used, its thickness shall be as small as possible to optimize its transmitting properties. This aspect is of major concern at high frequencies.

A.5.9 Transducer coupling

For precision measurements, the **ultrasonic transducer** should be coupled directly to the measurement liquid to avoid an impedance transformation by an additional coupling foil. This is particularly important for very sensitive high accuracy balances [18, 19] (Figure F.1). Avoiding the impedance transformation caused by the addition of a coupling foil is particularly important in measurements on highly resonant **ultrasonic transducers**.

Detailed technical drawings of a proven device for convenient measurements with a coupling membrane are given in [20]. They should work well for most practical measurements on broadband **ultrasonic transducers** provided that the anti-streaming foil is appropriately positioned as required in 5.8 and that its transmission coefficient is independently verified.

A.5.10 Calibration

Calibration using small weights of known mass is a check of the balance itself. Calibration using an ultrasonic reference transducer is a check of the entire measurement system including the **target**.

A.6 Measuring conditions

A.6.1 Lateral target position

For a convex-conical reflecting **target**, attention should be paid to the fact that the **target** may decentre under the action of the ultrasonic beam. The **target** may move into a region of lower intensity and the angle of incidence of the sound beam on the **target** may change.

This effect depends mainly on the radiated ultrasonic power and the distribution of local intensities as well as on the kind of suspension used for the **target**.

A.6.2 Transducer/target separation

The distance between the **ultrasonic transducer** surface and the **target**, or foil (if used) and **target**, should be as small as possible in view of the fact that **acoustic streaming** is caused by the ultrasonic absorption along the sound path.

NOTE The minimum possible separation may be limited by the shape or orientation of the target or transducer, or by consideration of heating or acoustic reflections amongst other effects.

An absorbing **target** can always be positioned near enough to the **ultrasonic transducer** to overcome any problem concerning a diverging field structure.

For a concave-conical reflecting **target**, it is essential to avoid any reaction of the reflected wave on the **ultrasonic transducer**. This type of **target** shall therefore be placed at a distance which avoids this interaction [21]. This minimum distance depends on the individual details and shall therefore be assessed individually.

The apex of a convex-type reflecting **target**, on the other hand, can be positioned virtually in contact with the face of the **ultrasonic transducer**, but this does not mean that the **target** covers the whole half-space into which the **ultrasonic transducer** radiates. Even if (in the case of a diverging field structure) almost all of the field reaches the convex-type cone, this may occur at angles of incidence which differ from those assumed in the plane-wave formula and may lead to a reduction of the actual **radiation force**. If there is any suspicion that the field of the **ultrasonic transducer** in question might not be collimated enough (this may occur primarily with low ka values, which means at low frequencies and/or with a small diameter of **ultrasonic transducer**), the distance between the **ultrasonic transducer** and the **target** should be varied and repeat measurements made. Any decrease in **radiation force** with increasing distance in excess of that caused by ultrasonic attenuation is an indication of an inappropriate **target** size or type.

In case an absorbing **target** is used for high power measurements, the transducer-**target** separation should not be too small. The absorbed ultrasound will heat the absorber. At small distances the transducer properties could change through direct heat transfer from the absorber.

A.6.3 Water

Degassed water at **output powers** exceeding 1 W is specified to avoid cavitation. At lower **output power** levels, degassed water is preferable for precision measurements but distilled water without additional degassing may be acceptable in many cases, if care is taken that air bubbles are not present on the faces of the **ultrasonic transducer** or the **target**.

NOTE 1 The amount of dissolved oxygen in the water increases with time, see Annex D and IEC/TR 62781. The speed of this increase depends on the tank dimensions and water disturbances.

NOTE 2 The use of an additive to suppress cavitation is described in IEC/TR 62781.

NOTE 3 If the water used is saturated with air, bubbles will form if the temperature of the water increases during the course of measurements. This is because the gas solubility decreases with temperature.

A.6.4 Water contact

The surfaces of the **ultrasonic transducer** surface, **target**, and foil (if used) should be wiped after being placed in the water tank to remove any films of air (taking care not to damage the surfaces). Wetting (water contact) can be further improved by storing these parts in degassed water before the measurements are taken. For some materials, several hours immersion may be required for ideal wetting.

NOTE Degassing an absorbing **target** together with the water prevents possible wetting problems of the absorber material, provided that the material is not damaged by being placed in a vacuum.

A.6.5 Environmental conditions

In addition, the measuring vessel should be almost closed to minimize thermal convection currents in the measuring liquid caused by cooling effects due to evaporation at the liquid surface.

In case of a measurement set-up as shown in Figure F.4, it may be difficult or impossible to close the measuring vessel and the resulting drift of the balance readout due to evaporation at the liquid surface needs to be corrected.

The temperature of the measuring liquid (water) should be measured. The value of the speed of sound in water, needed for calculating the power result, depends on the temperature. (See also A.7.10)

NOTE The influence of environmental vibrations and air flow can easily be observed in the balance readout.

A.6.6 Thermal drifts

This may also apply under certain circumstances to reflecting **targets**, though to a lesser extent.

The influence of target buoyancy changes is much reduced in the balance arrangement shown in Figure F.4 but even here, a recording of the balance readout as a function of time is recommended.

A.7 Measurement uncertainty

A.7.1 General

Void.

A.7.2 Balance system including target suspension

This requirement ensures that effect of the suspension wire penetrating the water surface is automatically taken into account.

A.7.3 Linearity and resolution of the balance system

Void.

A.7.4 Extrapolation to the moment of switching the ultrasonic transducer

Void.

A.7.5 Target imperfections

Strictly speaking, a knowledge of the momentum carried by all undesirable waves emanating from the **target** in all directions would be required to assess the influence of the **target** imperfections on the accuracy of the **radiation force** balance measurements. Since this knowledge is unavailable, in practice, a simplified plane-wave approach described below is considered to be sufficient. With the plane-wave assumption, the **acoustic radiation pressure** is equal to the total acoustic energy density. The wave transmitted by an absorbing **target** (as, for example, in the arrangement of Figure F.1a) in the forward direction leads to a reduction in the **radiation force**, the reduction being determined by the transmitted energy density, i.e. by the energy density existing behind the **target**. The magnitude of this effect can be determined by using the **target** as an obstacle and carrying out a **radiation force** measurement by means of an additional **target**, positioned immediately behind the original one. It should be noted that the reflection of the transmitted wave at the water surface in the arrangement shown in Figure F.1a will double the decrease in the measured **radiation force**.

The wave reflected or scattered back by an absorbing **target** leads to a **radiation force** increase that is determined by the reflected energy density. For a plane absorbing **target**, this effect can be assessed by comparing the pulse-echo signal with that from a perfect reflector. For a **target** with surface structure, however, this measurement determines only the spatially coherent component, and does not indicate the total reflected energy. In this case, the reflected energy would have to be assessed by scanning with a hydrophone and integrating the square of the measured pressure over the reflected field. Alternatively, other information about the properties of the absorber could be used to give an upper limit to the reflection (e.g. the reflectivity of an equivalent, plane version). In addition to increasing the measured **radiation force**, the reflection from the **target** can also act back on the **ultrasonic transducer** to change its output characteristics [8]. This interference effect can be minimized by slightly tilting the **target** or by using a better **target**. If the interference occurs, it will give rise to oscillations in the **radiation force**, which can be observed by varying the frequency or the **target**/**ultrasonic transducer** distance [8]. The uncertainty due to any residual interference effects can be assessed from the oscillation amplitudes.

NOTE The reflection or back-scattering properties of an absorbing **target** may depend on the angle of incidence. This is important in the case of an oblique beam (scanning). It can be checked by using a well-collimating transducer, placing it collinear with the force-measuring device and then tilting the absorbing **target** (but not the transducer and the balance). Ensure that the tilt angle is not too high so that the **target** fully intercepts the entire beam, even in the tilted position. For a perfect absorber, the result would not depend on the tilt angle.

For the case of reflecting **targets**, the previous discussion of the transmitted wave and its influence is also valid. The reflected waves, however, may come both from the **target** and from any lateral absorbers (see Figures F.1b, F.2, F.6) and so shall be considered more carefully.

Overall, the most reliable assessment of accuracy will be obtained by comparing measurements made with different **target** types. The acoustical properties of **targets** vary significantly with frequency and so any uncertainty assessment shall be made separately for each frequency of interest. It is particularly difficult to obtain a good **target** design for frequencies below 2 MHz.

To minimize the influence of coherent reflections, it is recommended to carry out and average 2 measurements at **target** distances separated by ¼ λ, where λ is the wavelength of the acoustic wave in the sound-propagating liquid (water).

A.7.6 Reflecting target geometry

As discussed in Clause B.2 the cone angle of a conical reflecting **target** has an influence on the measurement result. More specifically, if the cone half-angle of a convex-type reflector of nominally 45° lies within 45° ± 1°, the resulting power uncertainty is ± 3,5 %. If the cone half-angle of a concave-type reflector of nominally 63° (which means θ = 27°, following the notation given in Clause B.2) lies within 63° ± 1°, the resulting power uncertainty is ± 1,8 %.

NOTE Annex E gives additional information on the influence of the **target** size in case of diverging ultrasonic fields.

A.7.7 Lateral absorbers in the case of reflecting target measurements

Imperfections of the lateral absorbers in the arrangement of Figure F.1b, F.2, F.5b and F.6 give rise to reflected waves which return to the **target** and lead to an increase in the value of the measured **radiation force**. Here again, the reflected energy density is relevant under incoherent conditions and again, interference effects may occur (see A.7.5).

A.7.8 Target misalignment

This subclause applies if the **ultrasonic transducer** and the force-measuring device are collinear to each other but the angular alignment of the **target** is incorrect.

While the **radiation force** on a perfectly absorbing **target** according to the formula given in Clause B.2 is insensitive to a **target** tilt, in the case of the reflecting **target**, the measurement depends on the correct **target** orientation. For example, an angle uncertainty of ± 1° for a plane reflector at 45° leads to a power measurement uncertainty of ± 3,5 %. The influence of a misalignment in the case of a conical reflecting **target** cannot be given by a universal formula, but it will, in general, be much lower than that of a plane reflecting **target**, particularly when the **target** is centred over the beam. For a cylindrically symmetrical beam centred with respect to a 45° conical reflecting **target**, the sensitivity to angular misalignment is reduced still further.

An advantage of a concave-conical reflecting **target** is that, depending on the type of suspension it will centre itself symmetrically within the ultrasonic beam.

A.7.9 Ultrasonic transducer misalignment

This subclause applies if the **target** and the force-measuring device are collinear to each other but the **ultrasonic transducer** has an incorrect orientation or position.

In case of a perfectly absorbing **target** of sufficient size, the apparent **radiation force** is proportional to the cosine of the misalignment angle. In case of a 45° convex conical reflecting **target**, a maximum uncertainty due to misalignment of ± 3 % can be expected if maximum positioning and angular alignment errors of ± 3 mm and ± 3° are assumed [22], which appears to be realistic for an alignment by eye.

If the measurements are repeated and the **ultrasonic transducer** is removed from the apparatus between the measurements, a check of the random effects caused by **ultrasonic transducer** misalignment is included in the assessment. In addition, there may be a systematic transducer misalignment.

A.7.10 Water temperature

As a result of the temperature dependence of the speed of sound in water [23], an uncertainty in the temperature measurement of ± 1°C will result in a power measurement uncertainty of ± 0,2 %.

When power measurements have to be performed above 1 W a significant temperature rise can be expected. Care should be taken to take the actual temperature rise into account.

A.7.11 Ultrasonic attenuation and acoustic streaming

The power value as derived from the **radiation force** balance measurement refers to the **target** position at a given axial distance from the **ultrasonic transducer**. The quantity of interest, however, is often the radiated power with reference to the **ultrasonic transducer** surface. The additional uncertainty inferred in this case is discussed as follows.

This discussion counts mainly for **radiation force** measurement set-ups as given in Figures F.1, F.2, F.3, F.5, F.6 and F.7. For the measurement set-up as shown in Figure F.4 these effects seem to be less important but where effects have been observed their origin is unknown. For this measurement set-up the alternative approach as described further below should be used to perform the corrections.

There are two basic models accounting for the difference between the above-noted power values. The first one considers the influence of ultrasonic attenuation alone. In this case, the correction is made by including the exponential correction factor (see B.3.2). The second one includes the effects of the **acoustic streaming** along the free propagation path in front of the **target**. For an absorbing **target** under certain ideal conditions, the Borgnis theorem [24] states that the effects of attenuation and **acoustic streaming** cancel each other, and consequently no correction is necessary. The behaviour of real **targets** (both absorbing and reflecting ones) has been found to lie somewhere in between these two basic models [17]. It is therefore recommended to consider an uncertainty span which ranges from the uncorrected power value as measured by the balance to the value with the full attenuation correction [25]. This uncertainty contribution depends on the **target** distance and is particularly critical when the measurements are taken in the higher megahertz frequency range.

An alternative way is to measure the apparent power as a function of the **target** distance and to extrapolate the result back to zero distance by means of a regression algorithm based on a linear or exponential distance law. The measured values will not exactly fit the assumed distance law, i.e. there will be some experimental scatter, and so standard mathematical procedures can be used to estimate the uncertainty of the extrapolation result.

In the case of a non-planar **target** surface, it is difficult to define the effective **target** distance. Here, it is helpful to recall that the average height of a cone or pyramid is one-third of the peak height when measured from the base or two-thirds when measured from the apex. This rule can be applied when conically shaped reflecting **targets** or absorbing **targets** with pyramid-like shaped wedges are used. For a notionally uniform cylindrical beam incident on a convex conical **target**, the extra effective distance to the **target** (reckoned from the apex) is

$$2\,a\,/\,(3\tan\zeta)$$

where

a is the radius of the beam;

ζ is the half-angle of the cone.

A.7.12 Foil properties

Void.

A.7.13 Finite target size

In A.5.3, formulae are given for the minimum **target** size based on a 2 % criterion. If the actual **target** width is more than 50 % larger than the value determined by A.5.3, it is reasonable to assume an uncertainty contribution of only 1 % or even lower [14]. However, it is recommended to check the dependence of the **radiation force** on the **target** distance, in accordance with A.6.2, making due allowance for attenuation and **acoustic streaming.** (See 7.11)

Strictly speaking, the formulae referred to apply to an absorbing **target**. In A.5.3 and Annex E limitations are given for the use of convex-conical reflecting **targets**.

A.7.14 Plane-wave assumption

If the field has a divergent or convergent field structure, the plane-wave formulae of Clause B.2 are no longer strictly valid. Theoretical estimations of the magnitude of the errors due to the deviation from these formulae for focused fields are given in Clause B.5 and Clause B.6 (see [26, 27, 28]). Theoretical estimations of the magnitude of the errors due to the deviation from these formulae for divergent fields on an absorbing **target** are given in Clause E.1 (see [29, 30]). A discussion for divergent fields on convex-conical reflectors is given in Clause E.2.

A.7.15 Scanning influence

Void.

A.7.16 Environmental influences

The estimation of uncertainty due to environmental vibrations, air flow or temperature variations can be checked by repeating the measurements. Ideally, at least four sets of measurements should be carried out, preferably on different days, with each set consisting of at least four repeat measurements carried out consecutively.

A.7.17 Excitation voltage measurement

In general, the uncertainty in the measurement of the excitation voltage applied to the **ultrasonic transducer** is irrelevant for the **output power** measurement, provided the voltage remains constant. However, if **output power** measurements of the same **ultrasonic transducer** are taken at independent laboratories (e.g. for intercomparison purposes), the possible differences in the excitation voltage amplitude should be taken into account. As the **output power** is proportional to the square of the applied voltage, the **radiation conductance** G is usually formed in this case and the voltage uncertainty determined needs to be doubled when it is included in the overall uncertainty value of G.

NOTE If the excitation voltage is taken into consideration, it is its value as measured directly at the entrance of the **ultrasonic transducer** that is of relevance.

It is recommended that the excitation voltage be measured and recorded for the duration of every **output power** measurement for which the value of applied excitation voltage is used to establish a desired power level or to calculate the **radiation conductance**. Such data can be used to detect instabilities of various kinds.

A.7.18 Ultrasonic transducer temperature

The variation of the **output power** with the **ultrasonic transducer** temperature can be important when comparing measurements made at different times or in different places. Sometimes, this variation can be very significant (e.g. 5 % per °C), particularly with multilayered, impedance-matched **ultrasonic transducers**. The temperature variation may be caused by environmental changes or by heat dissipation within the **ultrasonic transducer**.

An increase in the transducer temperature may also produce thermal convection currents which may affect the balance reading.

These effects can be assessed by observing the **radiation force** as a function of time after energizing the **ultrasonic transducer**.

A.7.19 Nonlinearity

a) The linearity of the balance system including the **target** suspension can be checked by calibration by means of weights as a function of their mass value or by measurements with an **ultrasonic transducer** with known properties (7.2) and with the **target** closer than 10 mm to the **ultrasonic transducer**.

b) According to 6.3 and 6.4, water degassing and the absence of any bubbles are necessary. If there are air bubbles or cavitation activities in the ultrasonic field, the power measurement may be grossly incorrect. No general estimates can be given for these sources of error.

   More information on water degassing and cavitation can be found in Annex D.

c) Ultrasonic attenuation and **acoustic streaming** may involve nonlinearities. If the **target**/**ultrasonic transducer** distance or the smallest **target** distance in a distance variation experiment is less than 10 mm, it is sufficient to follow A.7.11. If the **target**/**ultrasonic transducer** distance or the smallest **target** distance in a distance variation experiment is 10 mm or higher, additional uncertainties due to nonlinearity are likely to occur, but no general estimate can be given here.

   It may appear that this effect can be checked with a reference **ultrasonic transducer** of known **output power**. It should be noted, however, that nonlinearities in ultrasonic attenuation and **acoustic streaming** may depend on the temporal waveform and on the peak pressure value, and that test results obtained with a reference **ultrasonic transducer** with a waveform different from that of the **ultrasonic transducer** to be measured are not therefore fully conclusive.

d) Apart from the effects dealt with in items a), b) and c) above, the theoretical **radiation force** relations themselves might be nonlinear and differ from the second-order formulae given in Clauses B.2 and B.5, where linear relationships between power and force are stated. However, in the **output power** range produced by current diagnostic and therapeutic ultrasonic equipment, and as long as no information to the contrary has been obtained, the **acoustic radiation force** should be regarded as a chiefly linear phenomenon with respect to the **output power**. Nonlinear deviations from the formulae given in Clauses B.2 and B.5 should be considered as negligible in comparison with the other uncertainty contributions [31].

A.7.20 Acceleration due to gravity

Void.

A.7.21 Other sources

It is recommended to check periodically whether the overall uncertainty as determined using the above guidelines is not influenced by any other sources of random scatter. This can be readily done by disassembling the measurement arrangement, reassembling it again and repeating the measurement at least three times. Also valuable are comparisons with other laboratories or **radiation force** balances or using different sources.

When the requirements of Clauses 5 and 6 are complied with and for transducers with $ka \geq 30$ or $kh_{\mathrm{h}} \geq 30$, an overall measurement accuracy of 10 % seems to be achievable [29, 32 – 35] in the frequency range from 1 MHz to 10 MHz, one of 20 % outside this frequency range and up to 20 MHz, and one of 30 % above 20 MHz. For transducers where $10 < ka < 30$ or $10 < kh_{\mathrm{h}} < 30$, the achievable overall measurement accuracy for frequencies around 1 MHz seems to be 20 %.

Error analyses for specific systems have been given in [25, 29, 33, 36]. Also, where calibrated reference **ultrasonic transducers** are available, test measurements with these are highly recommended [33, 34, 37].

Annex B
(informative)

Basic formulae

B.1 General

The **radiation force** measurements recommended in this standard are performed under open vessel conditions (Langevin condition), i.e. the irradiated fluid is in contact with the surrounding medium, which is subject to ambient pressure.

B.2 Plane-wave formulae

Under such conditions and for small amplitude plane ultrasonic waves, the **radiation pressure** appearing at the boundary surface between two media is equal to the difference between the total acoustic energy densities existing on both sides of the surface. This leads to the following formulae relating the **radiation force** component F on the **target** in the propagation direction of the incident wave to the acoustic **output power** P of the **ultrasonic transducer**:

For a perfectly absorbing **target**:

$$P = c\,F \tag{B.1}$$

For a perfectly reflecting **target**:

$$P = c\,F\,/\,(2\cos^2\theta) \tag{B.2}$$

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 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.

B.3 Assumptions involved

B.3.1 The above formulae involve the following assumptions:

B.3.2 The **target** is large enough to cover the whole cross-section of the ultrasonic beam, i.e. the amount of acoustic power emitted in such directions as to miss the **target** is negligible in comparison with the total acoustic power.

B.3.3 There is no ultrasonic absorption in the sound-propagating medium. If there is absorption, the symbol P in the above formulae represents the acoustic power in the position of the **target**. In order to convert it to the **output power** of the **ultrasonic transducer**, it has to be multiplied by $\exp(2\alpha z)$ where z is the distance between the **ultrasonic transducer** and the **target** and α is the amplitude attenuation coefficient of plane waves. The value of α in the megahertz frequency range is proportional to f^2 and is given, for example, by:

$$\alpha\,/\,f^2 = 2{,}3 \times 10^{-4}\ \text{MHz}^{-2}\ \text{cm}^{-1}\text{, for pure water at 23°C} \tag{B.3}$$

where f is the ultrasonic frequency (see [38], interpolated).

Prerequisites for the validity of this rule are the absence of additional damping due to finite amplitude distortions and the absence of an additional force on the **target** due to **acoustic streaming** (assuming a shielding foil is used).

B.4 Limits for unfocused fields

B.4.1 The above formulae are based on the plane-wave assumption. The field structure of **ultrasonic transducers**, even for non-focusing transducers, differs in general from that of a plane wave, mainly due to diffraction. However, the use of these formulae for non-focusing transducers is recommended for two reasons:

B.4.2 On the experimental side, they have never been found to be invalid for plane-piston **ultrasonic transducers** of sufficiently high ka or kh_h value, within the measurement accuracy of, typically, at least several per cent.

B.4.3 On the theoretical side [39], see also Equation (E.2) below, the plane-wave result has been found to be approximately valid in the case of a (unapodized) circular plane-piston source, provided its ka value is high enough ($k = 2\,\pi/\lambda$ being the circular wavenumber in the sound-propagating fluid and a being the radius of the **ultrasonic transducer**; the theoretical investigation has been restricted to the case of an absorbing **target**). For example, agreement amounts to 2 % (for continuous-wave excitation) if $ka \geq 35$, a condition which is usually fulfilled by **ultrasonic transducers**. A failure of the above formulae might be considered possible mainly in the range of low ka values (for a correction of this effect, see Annex E below).

Similar considerations apply to the case of a rectangular plane-piston source [27]. The plane-wave result is approximately valid provided the kh_h value is high enough (h_h being the harmonic mean of the transducer half-sides). Agreement amounts to 2 % (for continuous-wave excitation) if $kh_\mathrm{h} \geq 36$. The need for a correction might be expected mainly in the range of low kh_h values (see Annex E below).

B.5 Absorbing target in a focused field

B.5.1 Theoretical evidence has been found [26, 27] that the plane-wave formulae are not completely correct for focusing **ultrasonic transducers**. Instead, two **radiation force** expressions are given as follows. An ideally focusing transducer with constant normal velocity amplitude, a lossless fluid and a perfectly absorbing **target** of sufficient lateral size to cover the entire field are assumed, and diffraction effects at the beam edge are neglected.

For a circular transducer:

$$P = 2\,c\,F\,/\,(1 + \cos\gamma) \qquad \text{(B.4)}$$

where

γ is the focus (half-)angle, $\gamma = \arcsin(a/d)$ 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;

d is the geometrical focal length;

a is the radius of the active element of the **ultrasonic transducer**.

Expression (B.4) tends to the corresponding plane-wave formula for $\gamma \rightarrow 0$ or $d \rightarrow \infty$.

For a rectangular transducer:

$$P = c\,F \times numerator\,/\,denominator \qquad \text{(B.5)}$$

with $numerator = 2\arcsin(\sin\beta_x \sin\beta_y)$

$$denominator = \sin\beta_x \arctan(\cos\beta_x \tan\beta_y) + \sin\beta_y \arctan(\cos\beta_y \tan\beta_x)$$

where

β_x and β_y are the focus (half-)angles of a focusing **ultrasonic transducer** in the x-z and the y-z plane, respectively.

Expression (B.5) tends to the corresponding plane-wave formula for $\beta_x \rightarrow 0$ and $\beta_y \rightarrow 0$, or $d_x \rightarrow \infty$ and $d_y \rightarrow \infty$.

Strictly speaking, for the above formulae, the amplitude needs to be constant over a surface of constant phase. If the focusing effect is brought about by a curvature of the transducer surface alone, the transducer surface is a surface of constant phase and the validity of the above expressions thus is associated with the condition of constant transducer amplitude. This is not strictly true in other cases, i.e. when the focusing effect is brought about by other means such as phase steering. Slight deviations can then be expected, but the formulae are nevertheless recommended as approximations.

As long as no independent confirmation (theoretical or experimental) for the above evidence has been obtained, the differences mentioned should at least be regarded as possible and be accounted for by means of a contribution to the uncertainty estimate in the case of a focused field.

NOTE Formulae (B.4) and (B.5) neglect the diffraction at the beam edge, see [26, 27] (the same applies to Formula (B.6) below). This is similar to what is said in Clause B.4 above on the use of the plane-wave formulae from Clause B.2 in the case of unfocused fields. The diffraction effect depends on the temporal waveform of the field and on the amplitude distribution (apodization) across the transducer, and general statements are difficult.

B.5.2 Some examples of values following from Formulae (B.4) and (B.5) are given as follows:

For a circular, focusing transducer with a focus (half-) angle of $\gamma = 25°$, Formula (B.4) leads to:

$$P/cF = 1{,}049$$

For a rectangular, focusing transducer with $\beta_x = \beta_y = 25°$, Formula (B.5) leads to:

$$P/cF = 1{,}063$$

In the rectangular case with $\beta_x = \beta_y$, the correction needs to be greater than in the corresponding circular case with the same focus (half-)angle as the field from the corners is more inclined to the axis than in the circular case. This does not necessarily apply if β_x and β_y are unequal (see the example below).

For a rectangular, focusing transducer with $\beta_x = 25°$, $\beta_y = 15°$ or $\beta_x = 15°$, $\beta_y = 25°$, Formula (B.5) leads to:

$$P/cF = 1{,}043$$

Formula (B.5) applies to the case that there is focusing in both planes. If there is focusing only in one plane, e.g. only in the x-z plane, this can formally be expressed by $\beta_y = 0°$, but then Formula (B.5) becomes indeterminate. The problem can be solved using L'Hospital's rule which leads to $P/cF = 2 \sin\beta_x / (\beta_x + \sin\beta_x \cos\beta_x)$ or similar with β_y, where the angle in the denominator is to be expressed in radians.

For a rectangular transducer with $\beta_x = 25°$, $\beta_y = 0°$ or $\beta_x = 0°$, $\beta_y = 25°$, the formula mentioned leads to:

$$P/cF = 1{,}032$$

B.6 Reflecting target in a focused field

An approximate **radiation force** formula for a conical reflector in a focused ultrasonic field from a circular transducer is as follows [28]. Its derivation is based on the following assumptions:

- The ultrasonic field from a circular, spherically curved transducer in a lossless fluid is considered to consist of acoustic rays each of which is propagated along a straight line and is totally reflected at the **target** surface like a plane wave. γ is again the focus (half-) angle.
- The conical **target** is a perfectly hard or perfectly soft reflector. Its apex is placed on the field axis between transducer and focus. The **target** geometry is characterized by the angle θ as defined in Clause 4. Typical values for concave reflectors are between 25° and 30°. The value is to be understood as negative for convex reflectors; typically then $\theta = -45°$.
- The **target** covers the entire field, i.e. there are no rays that miss the **target**.
- The reflected rays freely propagate until infinity or are perfectly absorbed somewhere. There are no rays that return to the transducer. In the case of a concave **target**: There are no multiple reflections.

The formula then reads

$$P = 4\, c\, F \times \mathit{function}(\gamma, \theta)$$

with

$$\mathit{function}(\gamma, \theta) = (1 - \cos\gamma) / [(1 - \cos 2\gamma)(1 + \cos 2\theta) - (2\gamma - \sin 2\gamma) \sin 2\theta] \qquad \text{(B.6)}$$

NOTE 1 The angle γ appears in the above formula not only under trigonometric functions and is therefore to be used in radians.

NOTE 2 If $\theta = -45°$, then P/cF in accordance with Formula (B.6) has the value 0,98 (i.e. the difference between Formulae (B.2) and (B.6) amounts to 2 %) at a γ value that corresponds to $d = 32a$. This is the basis of the corresponding recommendation in 5.2.3.

It should be noted that the above expression applies to the pre-focal range and then goes through a Heaviside step function when the cone apex is moved through the focus.

The formula is based on a model which is not perfect and, therefore, is an approximation. Diffraction effects are neglected here, and also imaginary parts in the particle velocity which occur when acoustic rays are not parallel to one another. Local deviation from straight propagation (as, for example, due to diffraction) may result in an increase or decrease of the **radiation force** whereas in the absorber case, diffraction generally tends to decrease the **radiation force**.

NOTE 3 There is, however, experimental and computational evidence [40] to support the general trends indicated by the simple ray acoustic model and Formula (B.6). In this particular experiment with a convex-conical reflector of $\theta = -45°$, Equation (B.6) was approximately valid when the distance between transducer and cone apex was more than 20 mm and less than the focal length minus 10 mm. For distances smaller than 20 mm and obviously due to reflections between the transducer and cone, the measured force increased, up to a factor of approximately 2 for very small distances; for distances larger than the focal distance minus 10 mm, the measured force decreased progressively from the pre-focal value dealt with by Equation (B.6) to a lower, post-focal value.

NOTE 4 Experimental evidence has been found [41] that at least at high power levels (HITU), there are increased uncertainties with a conical reflector in a focused field as compared with an absorbing **target**.

NOTE 5 There is no corresponding formula for a conical reflector in a rectangular focused field. Conical reflectors should not be used in rectangular focused fields.

B.7 Absorbing target in an obliquely-incident or scanning field

B.7.1 General

In Clause B.2 the condition was mentioned that of the axis of the incident beam is collinear with the direction of the force-measuring device. This precondition is required for all formulae in Clauses B.2 to B.6. If, on the other hand, the axis of the incident beam is tilted so that there is a finite angle ψ between the beam axis and the direction of the force-measuring device, the **radiation force** as measured by the balance will be different from that in the collinear case. This is explained for the case of an absorbing **target** as follows. The following describes two different situations for how the measured **radiation force** is to be corrected. The remaining step of calculating the power from the corrected **radiation force** depends on the properties of the beam itself as dealt with in other subclauses of this standard.

B.7.2 Static, oblique beam

Let $F_\mathrm{B} = F(\psi)$ be the **radiation force** exerted by an oblique beam on an absorbing **target**, as measured by the balance, and let $F_\mathrm{A} = F(\psi = 0)$ be the **radiation force** of the same beam under collinear incidence; the relation then is [42]:

$$F_\mathrm{B} = F_\mathrm{A} \cos\psi \qquad \text{(B.7)}$$

It is a prerequisite that the beam in itself is identical in case A and case B, particularly with respect to amplitude, temporal waveform (duty cycle), focal parameters, etc. If the tilt angle ψ is known, Formula (B.7) can be used to correct the **radiation force** F_B obtained under oblique incidence and to convert it into F_A, the equivalent one under collinear conditions, namely by multiplying F_B with $1/\cos\psi$. The corrected **radiation force** F_A then serves to obtain the ultrasonic power P in accordance with any of the formulae in Clauses B.2 to B.5 or in Annex E.

B.7.3 Scanning beam

So far, two arrested beams A and B have been compared. In the scanning mode of a diagnostic device, the system produces a number of beams, say, n beams under n tilt angles ψ_i. It is assumed that (a) all beams and their power outputs are equal, irrespective of their direction, (b) each beam is activated for the same time interval before the system switches to the next beam, and (c) this time interval is much smaller than the reaction time of the **radiation force** balance so that the balance measures the temporal-average **radiation force** F. If F_A is the **radiation force** produced by the same beam if arrested and emitting all the time in the forward direction ($\psi = 0$), then

$$F = F_\mathrm{A}\, \overline{\cos\psi} \qquad \text{(B.8)}$$

with

$$\overline{\cos\psi} = \frac{1}{n}\sum_{i=1}^{n}\cos\psi_i \tag{B.9}$$

If the scan is over a large number of equidistant ψ values so that it can be considered a quasi-continuous scan from ψ_1 to ψ_2, then

$$\overline{\cos\psi} = \int_{\psi_1}^{\psi_2}\cos\psi\,\mathrm{d}\psi \bigg/ \int_{\psi_1}^{\psi_2}\mathrm{d}\psi = (\sin\psi_2 - \sin\psi_1)/(\psi_2 - \psi_1) \tag{B.10}$$

If the scan is in a symmetric way from $\psi_1 = -\psi_0$ to $\psi_2 = \psi_0$ then

$$\overline{\cos\psi} = \sin\psi_0/\psi_0 = \mathrm{sinc}\,\psi_0 \tag{B.11}$$

using the *sinc* function.

NOTE Values of ψ appearing in the denominator of Equations (B.10) or (B.11) are to be understood in radians.

The **radiation force** F obtained in scanning mode is to be converted by multiplication with $1/\overline{\cos\psi}$ into F_A, the equivalent one under permanently collinear conditions. The corrected **radiation force** F_A then serves to obtain the ultrasonic power P in accordance with any of the formulae in Clauses B.2 to B.5 or in Annex E.

For the measuring conditions to be comparable for all beams, the **target** size needs to be sufficiently large, see 5.3, and the acoustic properties of the absorbing **target** need to be sufficiently independent of the angle of incidence.

If the beam characteristics and the measuring conditions are not equal for all beams, appropriate weights will have to be introduced in the averaging process leading to $\overline{\cos\psi}$, but no general recommendation can be given here.

As an example of the above formulae, assume that a beam is scanning quasi-continuously between –30° and 30°. Then Equation (B.11) leads to F_A / F = 1,047. The question of how F_A is to be converted into the ultrasonic power P depends on the other properties of the beam, namely diffraction and focusing. If it is assumed that the beam in itself is focused with $\beta_x = \beta_y = 25°$ (see B.5.2), the two correction factors from Clauses B.5 and B.7 have to be multiplied, leading to Pc/F = 1,113 in this example, whereby a diffraction influence ([26, 27]) analogous to Clause B.4 and Annex E has not yet been taken into account (see also the note at the end of B.5.1).

B.8 Summary for absorbing target

When an absorbing **target** of almost infinite lateral size is used, there are three effects that independently lead to a decrease of the **radiation force** from the plane-wave value of Equation (B.1), namely (a) diffraction which is covered in E.1.1 and E.1.2, (b) focusing which is covered in Clause B.5 and (c) scanning which is covered in Clause B.7. In case of a **target** with insufficient lateral size, another potential decrease of the measured **radiation force** may happen which is covered in A.5.3.1, A.5.3.2 and A.5.3.3. In practice, several of these effects may occur at the same time and should all be taken into account and corrected for.

Annex C
(informative)

Other methods of ultrasonic power measurement

Many other **radiation force** methods have been applied, as for example the torsion balance [43] or the devices using modulated **radiation force** [25, 44]. The modulated **radiation force** balance can be used with any **ultrasonic transducer** capable of operation with modulated or tone-burst excitation. A large family of devices is formed by the float-method instruments which are typically intended for the range of power of the order of watts used in ultrasonic therapy. In the basic design [21] a cone-shaped reflector moves under the action of the **radiation force** into a denser liquid. Numerous modifications and improvements of the principle can be found in the literature [45 – 49]. A very sensitive immersion balance, suitable for measurements in the microwatt range, has been described [50]. **Radiation force** balance measurements in the HITU power range are dealt with in the future IEC 62555.

Other methods which differ from the **radiation force** principle are the scanning of the ultrasonic field by means of a calibrated hydrophone (planar scanning) (see IEC 62127-1 and IEC 62127-2) [51] and light diffraction (Debye-Sears) [1, 52], buoyancy change (see future IEC 62555) [53, 54] and calorimetric methods [1, 3, 55].

Annex D
(informative)

Propagation medium and degassing

It is well established that measurements of ultrasonic power, particularly at frequencies of 1 MHz and below, can be strongly affected by acoustic cavitation. Cavitation is the growth, oscillation and collapse of previously-existing gas or vapour-filled microbubbles in a medium. During ultrasonic power measurements, these bubbles will scatter the ultrasound from the transducer under test, causing instabilities and underestimates of true power. There is thus a need to know when cavitation is occurring during power measurements, and also to define suitable media in which the effects of cavitation may be minimized.

A measurement method to detect the onset of cavitation is described in [29]. Specifically, the onset of inertial cavitation is often characterized by the presence of the subharmonic of the fundamental operating frequency. An example of an acoustic spectrum acquired using a needle hydrophone is presented in [29].

Possible methods to degas the water are listed in [30] and IEC/TR 62781.

Where the use of degassed water is recommended, measurement of the dissolved O_2-concentration will give sufficient information about the amount of dissolved gas in the water.

Annex E
(informative)

Radiation force measurement with diverging ultrasonic beams

E.1 Correction and uncertainty, divergent fields impinging on an absorbing target

E.1.1 Circular source transducer

The method commonly applied to measure the **radiation force** F and to calculate the ultrasonic power P is based on the assumption that the waves are plane. More realistic field models from the literature [26] were studied as a part of a European collaborative project and reported in Annex B of that study [29]. It can generally be stated that the structure of a real, circular, unfocused field is most likely between that of a plane wave and that of a circular plane piston field. In the case of a perfectly absorbing **target** of infinite cross-sectional size the relevant formula is

$$\frac{P}{c\,F}=1 \tag{E.1}$$

for a plane wave and

$$\frac{P}{c\,F}=\frac{1-J_1(2\,ka)/ka}{1-J_0^2(ka)-J_1^2(ka)} \tag{E.2}$$

for a circular plane piston source,

where

c is the speed of sound,

k is the circular wavenumber,

a is the transducer radius,

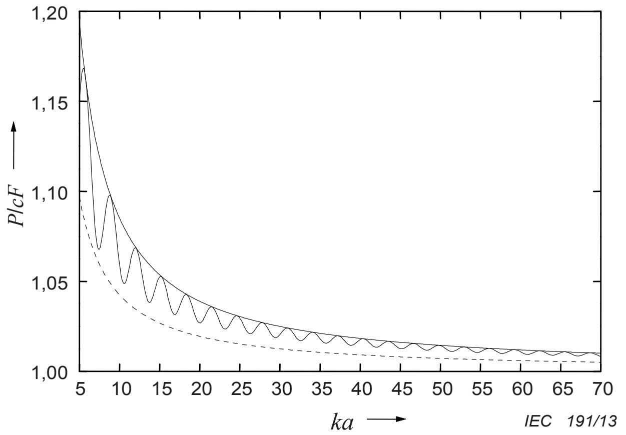
J stands for Bessel functions.

In Figure E.1 the oscillating curve represents the Bessel function formula of Equation (E.2). The maxima can be connected by a smooth curve according to the formula ("peak" approximation):

$$\frac{P}{cF}=fct(ka)=1+\frac{0{,}653\,1}{ka}\left(1+\frac{1{,}407}{(ka)^{2/3}}\right) \tag{E.3}$$

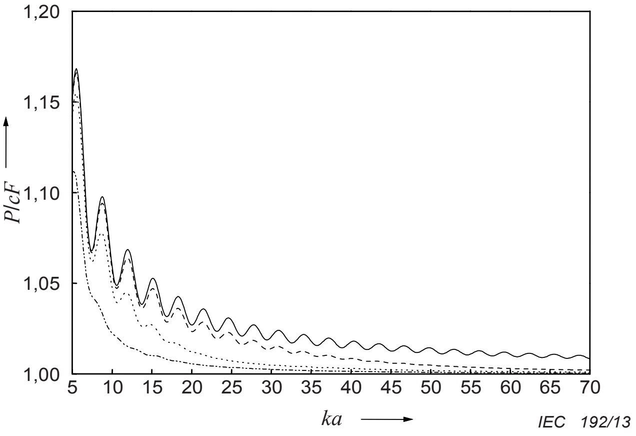
which is given as the unbroken line in Figure E.1.

This curve applies only to a piston source; for other amplitude distributions, particularly for transducers with an amplitude shading (apodization) at the rim, it can be expected that the curve lies somewhere between P/cF = 1 (plane wave) and the piston curve.



NOTE With "peak" approximation (unbroken line) and the central, half-way curve (broken line) representing the correction factor *corr*.

Figure E.1 – Piston result (oscillating curve) for *P/cF* as a function of *ka*



NOTE With ε = 0 (piston) (solid); ε = 0,1 (dash); ε = 0,25 (dot); ε = 0,6 (dash/dot)

Figure E.2 – *P/cF* as a function of *ka* for four different pseudo-trapezoidal amplitude distributions

Calculation results confirming this are presented in Figure E.2. A pseudo-trapezoidal distribution is considered and the decrease in the vibrational amplitude towards the edge of the transducer is assumed not to be linear as in [26], but is given in a quadratic manner in accordance with the following formula:

$$\frac{v(R)}{v_0} = \left\{ \begin{array}{ccc} 1 & \text{for} & 0 \le R \le a_1 \\ \dfrac{a_2^2 - R^2}{a_2^2 - a_1^2} & \text{for} & a_1 \le R \le a_2 \\ 0 & \text{for} & a_2 \le R \end{array} \right\} \tag{E.4}$$

in which R is the lateral distance from the transducer centre. It assumes that the particle velocity amplitude v is equal to a constant v_0 up to a characteristic radius $R = a_1$ and that it then monotonically decreases towards zero until the second characteristic radius $R = a_2$ is reached, and that it remains zero beyond a_2. The effective transducer radius a is defined here simply as that value of R for which the velocity amplitude is $v_0/2$ which means

$$\frac{v(a)}{v_0} = \frac{1}{2} \tag{E.5}$$

This is similar to the definition used in [26]. Equations (E.4) and (E.5) lead to

$$a^2 = \frac{a_1^2 + a_2^2}{2} \tag{E.6}$$

Every pseudo-trapezoidal distribution can be characterized by a parameter ε (referred to as α in [26]) which is as in [26] the relative width of the amplitude fall-off zone near the transducer rim according to

$$\varepsilon = \frac{a_2 - a_1}{a} \tag{E.7}$$

Four different pseudo-trapezoidal amplitude distributions are considered here, and are displayed in Figure E.2 using different printing types as follows: $\varepsilon = 0$ (piston) (solid); $\varepsilon = 0{,}1$ (dash); $\varepsilon = 0{,}25$ (dot); $\varepsilon = 0{,}6$ (dash/dot). The results for the distributions with $\varepsilon > 0$ can be seen to lie between the piston curve and the plane-wave result $P/cF = 1$ (see also [26]).

For this reason, the mean value of 1 (plane-wave value) and Equation (E.3) can be considered to be the best approximation to P/cF in the case of an unknown amplitude distribution. This is shown in Figure E.1 by the broken line and represents the correction which can be applied by multiplying the plane-wave measurement results with the correction factor

$$corr = \frac{1 + fct(ka)}{2} \tag{E.8}$$

which increases the result from the value $P/cF = 1$ to that represented by the central, broken line in Figure E.1 and by assuming an uncertainty $\pm u$ which covers the full space between the value $P/cF = 1$ and the unbroken "peak" connection line in Figure E.1.

It is recommended to use this approximation. In practice the most suitable effective radius a should be taken. For transducers used in physiotherapy the radius shall be calculated from the effective radiation area value (A_{ER}) as given in IEC 61689. For other transducers the radius value a shall either be determined by means of hydrophone measurements or by means of a geometric measurement of the element, or group of elements, dimension. The correction factor $corr$ is calculated as a function of ka in accordance with

$$corr = 1 + \frac{0{,}6531}{2\,ka}\left(1 + \frac{1{,}407}{(ka)^{2/3}}\right) \tag{E.9}$$

This factor $corr$ compensates for the (usually small) effects of non-plane field structure (beam divergence) in the case of **radiation force** measurements with absorbing **target**. It can be applied to the acoustic power values obtained.

As the field structure of the transducers under test is not known in sufficient detail to calculate the true correction factor in each individual case, the correction is affected by an uncertainty. It is based on the assumption of a rectangular distribution extending from $P/cF = 1$ to the value of Equation (E.3).

It should be noted that the treatment above is appropriate for an absorbing **target**. No correction or uncertainty is available for use when a reflecting **target** is used for measurements.

E.1.2 Rectangular source transducer

The provisions of E.1.1 can be transferred accordingly to the case of a rectangular source transducer, with only the numbers in the equations changed. The final Formula (E.9) is changed to

$$corr = 1 + \frac{0{,}668}{2\,kh_{\mathrm{h}}}\left(1 + \frac{1{,}33}{(kh_{\mathrm{h}})^{2/3}}\right) \tag{E.10}$$

NOTE (Applies to E.1.1 and E.1.2.) The effects described in E.1.1 and E.1.2 are due to diffraction at the beam edge which is a general effect that occurs in any case, however, to a larger extent at small ka or kh_{h} values. Subclauses E.1.1 and E.1.2 do not deal with intentional beam divergence due to de-focusing based on phase steering or transducer curvature or the use of a divergent lens.

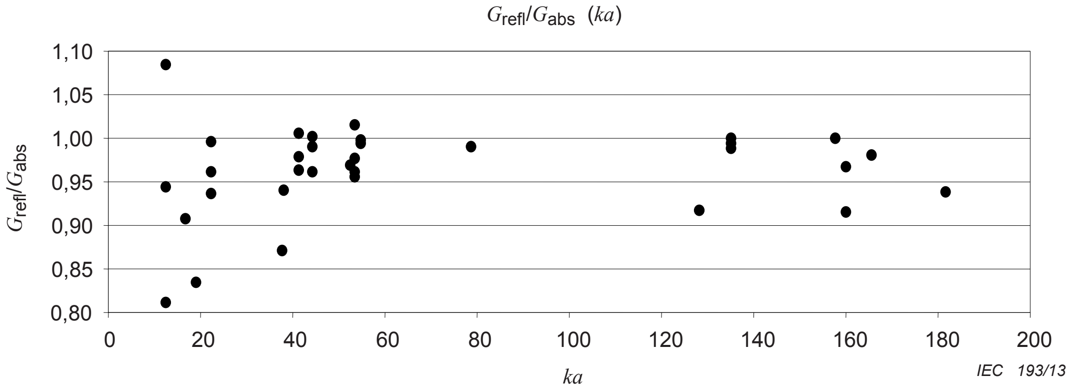
E.2 Correction and uncertainty, divergent fields impinging on a reflecting target

Although at the moment no field correction method is known for a convex-conical reflector in a divergent field, some guidance will be given for the case of a circular transducer.

The basic formula to calculate power for a perfectly reflecting **target** in a collimated field is given in Clause B.2.

From this it can be predicted that the acoustic power will be underestimated for any diverging beam. The amount of underestimation depends strongly on the pressure distribution in the beam and the divergence of the beam. For a convex-conical reflector with a cone half-angle of 45°, it can be calculated that a 5° underestimation of the angle of incidence already results in a underestimation of the power of 17 %. In practice, not all force contributions would have the same angle of incidence so this approach would be too conservative. The result of a comparison between acoustic power measurements in the range from 1 W to 20 W performed with convex-conical reflectors with a cone half-angle of 45° and absorbing **target**s is shown in Figure E.3 [29]. From this figure it follows that this type of convex-conical reflector systematically underestimates the emitted power.

It can also be deduced that below a ka value of 30 the uncertainty rises to unacceptable values. One of the most important reasons for this behaviour is explained below.



NOTE Reflecting target with a cone half-angle of 45°, results for 11 different circular transducers to be used in physiotherapy and 3 different laboratories.

Figure E.3 – Ratio of the radiation conductance G as obtained using a convex-conical reflecting target to an absorbing target versus the value of ka [29]

E.3 Target diameter

There are formulae for the minimum **target** radius r as a function of the axial **target** distance z, and all this depending on ka or kh (see 5.3). Strictly speaking, these formulae apply to a plane absorber but it may be of value to extend this to other **target** types.

r 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. If the calculation is applied to the case of a 45° convex-conical reflector, it turns out that there is a certain limiting ka or kh value below which the requirements of these formulae can never be fulfilled, irrespective of the reflector size and even if the reflector apex is as close as possible, namely in contact with the transducer surface. This limiting value is ka = 17,4 or kh_{h} = 17,4.

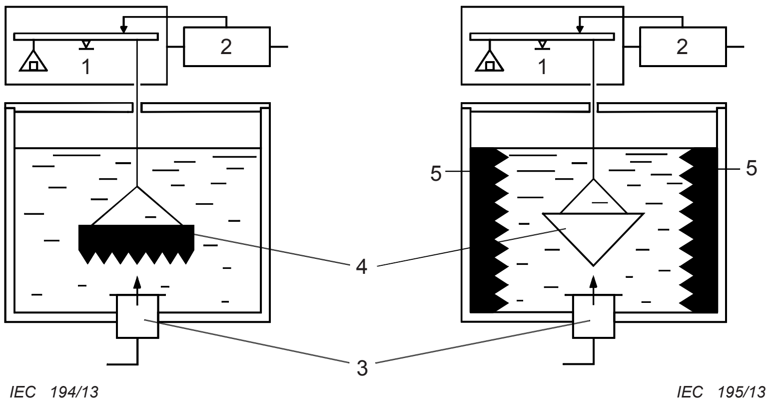
Annex F
(informative)

Limitations associated with the balance arrangements

F.1 Balance arrangements

The most frequently used balances are presented and described as follows. They are identified by the way the **target** is attached to the balance pan:

Arrangement A:	where the **target** is hanging under the balance, the water tank is not in contact with the balance pan, the transducer radiates upwards. For example, through a hole in the bottom of the water tank (Figure F.1).
Arrangement B:	where the **target** is suspended via a bridge to the balance pan underneath, the water tank is not in contact with the balance pan, the transducer radiates downwards from the top into the water tank (Figures F.2 and F.3).
Arrangement C:	where the **target** rests on the bottom of a water tank which rests on the balance pan, the transducer radiates downwards from the top into the water tank (Figure F.4).
Arrangement D:	where a flat reflecting **target** is suspended at an angle via a bridge to the balance pan, the water tank is not in contact with the balance pan, the transducer radiates downwards from the top into the water tank.
Arrangement E:	where the **target** is hanging via a bridge under the balance, to create space for transducer mounting, the water tank is not in contact with the balance pan, the transducer radiates downwards (Figure F.5).
Arrangement F:	with a horizontal beam, and where the **target** is suspended beneath a support, with means to detect its position; a means is also supplied to provide a measured opposite and equal force to retain the **target** in a null position (Figures F.6 and F.7).



IEC 194/13 IEC 195/13

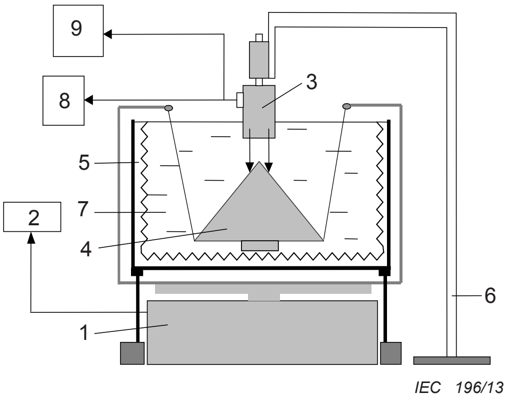
Figure F.1a – Absorbing target

Figure F.1b – Reflecting target

Key

1	balance
2	balance control
3	transducer
4	target
5	lateral absorber

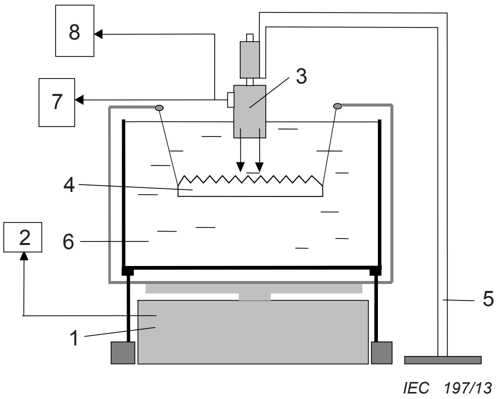
Figure F.1 – Arrangement A



Key

1	balance
2	balance control
3	transducer
4	target
5	lateral absorber
6	transducer support
7	water vessel
8	generator and amplifier
9	voltage measurement

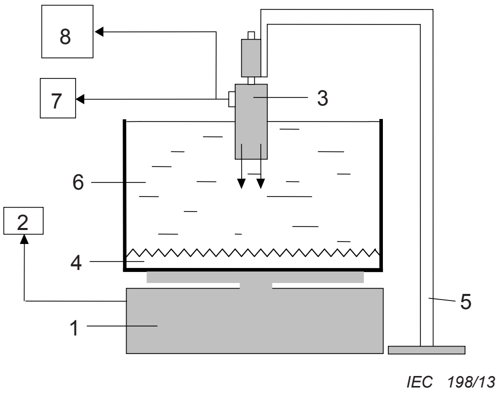
Figure F.2 – Arrangement B, with convex-conical reflecting target



Key

1	balance
2	balance control
3	transducer
4	target
5	transducer support
6	water vessel
7	generator and amplifier
8	voltage measurement

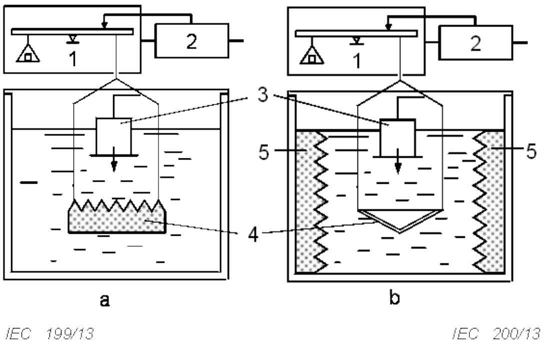
Figure F.3 – Arrangement B, with absorbing target



Key

1	balance
2	balance control
3	transducer
4	target
5	transducer support
6	water vessel
7	generator and amplifier
8	voltage measurement

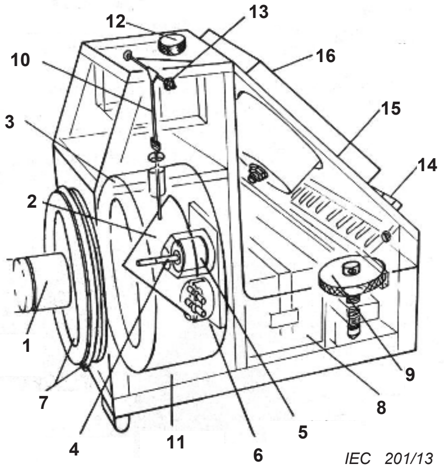
Figure F.4 – Arrangement C, with absorbing target



Key

1	balance
2	balance control
3	transducer
4	target
5	lateral absorber

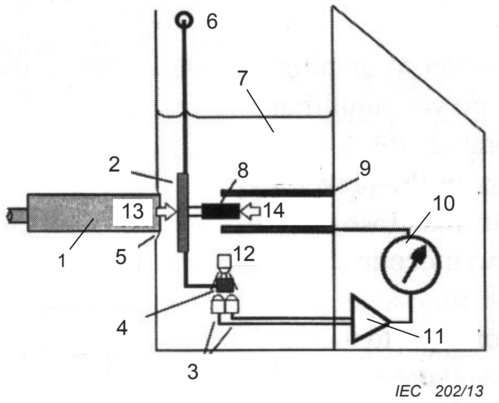
Figure F.5 – Arrangement E, with absorbing (a) or concave-conical reflecting (b) target



Key

1	transducer
2	hollow conical target
3	composite total absorber
4	force-balance magnet
5	force-balance coil
6	opto diode-transistor null detectors
7	PVC membrane and retaining O-ring
8	lead-acid battery
9	levelling zero wheel
10	suspension arm
11	water-filled chamber
12	water filter cap
13	jewelled bearings
14	range switches, electronic section, power meter

Figure F.6 – Arrangement F, with convex-conical reflecting target



Key

1	transducer
2	absorbing target
3	photo transistors
4	opaque flag
5	thin plastic window
6	pivot axis
7	water
8	magnet
9	coil
10	current meter
11	amplifier
12	led
13	radiation force
14	magnetic force

Figure F.7 – Arrangement F with absorbing target

All balance arrangements can be equipped with either an absorbing or a reflecting **target**. Although balance arrangement C can be equipped with a reflecting **target**, only the arrangement equipped with an absorbing **target** is discussed in this annex. Due to its construction balance arrangement A is more appropriate for use as primary standard than for use in an industrial environment.

F.2 Limitations associated with the balance arrangements

Although all balance arrangements as presented are well suited to measure the ultrasonic power, each arrangement has its own advantages and disadvantages when used in the industrial environment or as primary standard. They are given in Table F.1 below.

Table F.1 – Advantages and disadvantages of different arrangements

	Arrangement with absorbing target						**Arrangement with reflecting target**						**Comment**
	A	**B**	**C**	**D**	**E**	**F**	**A**	**B**	**C**	**D**	**E**	**F**	
Advantage	✓	✓			✓		✓	✓				✓	Relatively inexpensive balance
			✓										Very suitable for general use
						✓						✓	Design enables robust portable balance construction
	✓						✓						Uncomplicated mechanical construction needed to support the **target**
			✓										No mechanical construction needed to support the **target**
			✓										Easy access
		✓	✓					✓	✓				Easy exchangeability of transducer
											✓		The concave **target** will centre itself in the ultrasonic beam
			✓										Insensitive to **target** misalignment
							✓	✓			✓		Heat at high power levels will be redistributed at the walls of the tank
						✓						✓	Thermally generated forces are perpendicular to measurement direction
Disadvantage							✓	✓			✓	✓	Diverging ultrasonic beams ($ka < 30$ or $kh_{\mathrm{h}} < 30$) cannot be measured accurately
	✓						✓						Provisions are needed for ultrasound to radiate from the bottom upwards
						✓						✓	Coupling membrane compromise between strength and acoustic loss
	✓						✓						Convection currents from transducer face to **target**
							✓	✓	✓	✓	✓	✓	Need to include absorbing tank lining, which also makes the tank non transparent
							✓						**Target** displacement will be sensitive to non-uniform ultrasonic beams
	✓	✓	✓		✓	✓			✓				Heat, due to ultrasound absorption, may change the acoustic properties of the **target**
	✓						✓						Heat transport from transducer face to **target**
	✓	✓			✓		✓	✓			✓		**Target** suspension wires can be easily damaged
								✓					Mechanical construction needed to support the **target** and avoid **target** displacement due to non-uniform ultrasonic beams.
			✓						✓				As the tank including the **target** is placed on the balance pan the weighing range has to be wide, maintaining a high sensitivity. This results in an expensive balance type. The minimum measurable power will be about 20 mW
						✓						✓	Direct water coupling requires specialised apertures
						✓						✓	Calibration by gravitational force requires added balance arm

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IEC 62127-1, *Ultrasonics – Hydrophones – Part 1: Measurement and characterization of medical ultrasonic fields up to 40 MHz*

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

IEC 62127-3, *Ultrasonics – Hydrophones – Part 3: Properties of hydrophones for ultrasonic fields up to 40 MHz*

IEC 62555, *Ultrasonics – Power measurement –High intensity therapeutic ultrasound (HITU) transducers and systems*[2]

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