SLOVENSKI STANDARD
SIST EN 61161:2002

01-september-2002

Ultrasonic power measurement in liquids in the frequency range 0,5 MHz to 25 MHz (IEC 61161:1992)

Ultrasonic power measurement in liquids in the frequency range 0,5 MHz to 25 MHz

Ultraschall-Leistungsmessung in Flüssigkeiten im Frequenzbereich von 0,5 MHz bis 25 MHz

Mesurage de puissance ultrasonore dans les liquides dans la gamme de fréquences de 0,5 MHz à 25 MHz

Ta slovenski standard je istoveten z: **EN 61161:1994**

ICS:

17.140.50	Elektroakustika	Electroacoustics

SIST EN 61161:2002 **en**

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 61161

August 1994
\+ A1
February 1998

UDC 534.6-8:534.83:534.321.9
ICS 17.140.50
Descriptors: Ultrasound, acoustic output, measurement

English version

Ultrasonic power measurement in liquids in the frequency range 0,5 MHz to 25 MHz

(includes amendment A1:1998)
(IEC 61161:1992 + A1:1998)

Mesurage de puissance ultrasonore dans les liquides dans la gamme de fréquences de 0,5 MHz à 25 MHz
(inclut l'amendement A1:1998)
(CEI 61161:1992 + A1:1998)

Ultraschall-Leistungsmessung in Flüssigkeiten im Frequenzbereich 0,5 MHz bis 25 MHz
(enthält Änderung A1:1998)
(IEC 61161:1992 + A1:1998)

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CENELEC

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

Central Secretariat: rue de Stassart 35, B-1050 Brussels

Ref. No. EN 61161:1994/A1:1998 E

Foreword

The CENELEC questionnaire procedure, performed for finding out whether or not the International Standard IEC 1161:1992 could be accepted without textual changes, has shown that no common modifications were necessary for the acceptance as a European Standard.

The reference document was submitted to the CENELEC members for formal vote and was approved by CENELEC as EN 61161 on 8 March 1994.

The following dates were fixed:

—	latest date of publication of an identical national standard	(dop) 1995-03-15
—	latest date of withdrawal of conflicting national standards	(dow) 1995-03-15

Annexes designated "normative" are part of the body of the standard. Annexes designated "informative" are given only for information. In this standard, Annex A and Annex ZA are normative and Annex B and Annex C are informative.

Foreword to EN 61161:1994/A1:1998

The text of document 87/113/FDIS, future amendment 1 to IEC 61161:1992, prepared by IEC TC 87, Ultrasonics, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as amendment A1 to EN 61161:1994 on 1998-01-01.

The following dates were fixed:

—	latest date by which the amendment has to be implemented at national level by publication of an identical national standard or by endorsement	(dop) 1998-10-01
—	latest date by which the national standards conflicting with the amendment have to be withdrawn	(dow) 1998-10-01

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Introduction

A number of measuring methods exist for the determination of the total radiated power of ultrasonic transducers ([1][1] to [3][1], see also Annex B). The purpose of this International Standard is to establish methods of measurement of ultrasonic power in liquids in the 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. In addition, the radiation force measuring devices are easy to handle and to calibrate.

This standard enumerates the sources of errors and describes a systematic step-by-step procedure needed to assess overall measurement uncertainties.

1 Scope

This International Standard

- — specifies a method of determining the total radiated 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;

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

- — provides information on assessment of overall measurement uncertainties.

This International Standard is applicable to:

- — the measurement of ultrasonic power based on the use of a radiation force balance in the frequency range from 0,5 MHz to 25 MHz;
- — the measurement of total ultrasonic power of transducers with well-collimated beams;
- — the use of radiation force balances of the gravimetric type.

NOTE The titles of other publications referred to in this Standard are listed in Annex C.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 50(801):1984, *International Electrotechnical Vocabulary (IEV), Chapter 801: Acoustics and electro-acoustics.*

IEC 150:1963, *Testing and calibration of ultrasonic therapeutic equipment.*

IEC 1101:1991, *The absolute calibration of hydrophones using the planar scanning technique in the frequency range 0,5 MHz to 15 MHz.*

3 Definitions

3.1
acoustic streaming

steady-state fluid motion which develops under certain conditions in a sound field

3.2
far field

sound field at a distance from the source where the sound pressure decreases monotonically with increasing distance from the source. In general, this is the region of the sound field where the specific acoustic impedance, i.e. the complex ratio of sound pressure to particle velocity, is substantially equal to ρc, ρ being the density and c the velocity of sound in the sound-propagating medium

3.3
free field

a sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on the sound waves [IEV 801-03-28 modified.]

3.4
near field

sound field at distances from the source smaller than the distance at which the **far field** begins. In general, this is the region of the sound field where the complex specific acoustic impedance differs appreciably from ρc

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[1] The figures in square brackets refer to Annex C — Bibliography.

3.5
output power

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

Symbol: *P*

Unit: watt, W

3.6
radiation force; acoustic radiation force

time-average force acting on a body in a sound field and caused by the sound field; or, more generally: time-average force in a sound field, appearing at the boundary surface between two media of different acoustic properties

Symbol: *F*

Unit: newton, N

3.7
radiation pressure; acoustic radiation pressure

radiation force per unit area

3.8
target

a device specially designed to be inserted into the ultrasonic field and to serve as the object on which the **radiation force** is to be measured

3.9
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

4 List of symbols

a = radius of a source **ultrasonic transducer**

c = speed of sound (usually in water)

d = geometrical focal length of a focused **ultrasonic transducer**

F = **radiation force** on a **target** in the propagation direction of an ultrasonic wave

g = acceleration due to gravity

k = (= $2\pi/\lambda$) circular wavenumber

P = **output power** of an **ultrasonic transducer**

s = (= $x\,\lambda/a^2$) distance normalized to the **near-field** length

x = distance between a **target** and an **ultrasonic transducer**

α = amplitude attenuation coefficient of plane waves in a medium (usually water)

γ (= arc sin a/d) focus angle of a focused **ultrasonic transducer**

θ = angle between propagation direction of an ultrasonic wave and the normal to a reflecting surface of a **target**

λ = ultrasonic wavelength.

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 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, according to the formulae given in Annex A. Calibration can be carried out by means of small precision weights of known mass.

5.2 Target type

The **target** shall have known acoustic properties, these being relevant to the details of the relation between ultrasonic power and **radiation force**. Usually, the aim is to approach most closely one of the two extreme cases: perfect absorber or perfect reflector [4]. The compressibility should be as low as possible in order 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**.

5.2.1 *Absorbing target*

An absorbing **target** (see Figure 1) shall have:

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

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

Figure 2 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. 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.

5.2.2 *Reflecting target — General*

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 which are normally realized by means of air-backed thin metal plates cannot be applied. Using solid metal plates as reflectors, that are adjusted under an angle of 45° to the sound beam axis, may cause an enormous error [5].

Cone-shaped reflectors made of thick-walled hollow bodies or of air-backed thin metal plates are applicable. 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** [4].

5.2.3 *Reflecting target — convex*

A conical reflector of the convex type is shown in Figure 3. The cone half-angle is typically chosen to be 45°, so that the reflected wave leaves at right angles to the ultrasound beam axis.

5.2.4 *Reflecting target — concave*

A conical reflector of the concave type is shown in Figure 4. 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.

5.3 Target diameter

The **target** diameter shall be large enough to intercept all significant parts of the field, and shall be at least 1,5 times larger than the appropriate dimension (e.g. the diameter) of the **ultrasonic transducer**. The necessary diameter value depends on the field structure and on the distance of the **target** from the **ultrasonic transducer**.

In the following, an assessment formula [6] is given for the minimum value of the **target** radius b which would lead to a **radiation force** which amounts to at least 98 % of the **radiation force** that would exist if the **target** were of infinite cross-sectional size (i.e. giving an error of less than 2 %). 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:

$$b = a\,[1/(1 + 0{,}53\,\tau_1 s) + \tau_1 s] \qquad (1)$$

with

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

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

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

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

where

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

2 is the ultrasonic wavelength in the propagation medium;

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

$s = x\,\lambda/a^2$ is the distance between the **target** and the **ultrasonic transducer** normalized to the **near-field** length.

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

By way of precaution, b should never be reduced below 1,5 a, even if this were possible according to the above equation.

5.4 Microbalance/Force measuring system

The **radiation force** balance is understood in this standard to be a gravimetric balance and, hence, the beam orientation is vertical.

NOTE A horizontal beam orientation may potentially be of interest since thermal effects, such as convection currents and changes in buoyancy, should be reduced in that case. A measurement set-up with horizontal beam orientation is described in [7].

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 [8] 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 $g = 9{,}81\ \mathrm{m \cdot s^{-2}}$, in order 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 according to the formulae given in Annex A, the use of a sound velocity value in metres per second, as for example $c = 1\,491\ \mathrm{m \cdot s^{-1}}$ in pure water at 23 °C, then yields a power in microwatts (or in milliwatts, respectively).

5.5 System tank

If a reflecting **target** is used, an absorbing lining of the measuring vessel shall be used.

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 **freefield** value.

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 should be designed to minimize the effect of surface tension.

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. Disturbing forces may be of the order of 0,1 µN. 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 4.

NOTE Platinum-iridium wire of diameter 50 µm is suitable.

5.7 Transducer positioning

The **ultrasonic transducer** mount shall be such as to ensure stable and reproducible positioning of the **ultrasonic transducer** with respect to the **target**.

5.8 Anti-streaming foils

If the energy absorption along the sound path cannot be neglected (long sound path and/or high frequency [9]) **acoustic streaming** can take place. To reduce streaming effects in the measuring liquid, thin plastic foils are often put into the sound path. When using these foils two boundary conditions shall be fulfilled: the foil shall be positioned close to the **target** and shall not be oriented parallel to the surface of the **ultrasonic transducer** [10].

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.

If a foil is used its thickness shall be as small as possible in order to optimize its transmitting properties. This aspect is of major concern at high frequencies. The transmission coefficient should be known from theory or experiment and a correction shall be applied if its influence is too high.

The foil shall be positioned at a slightly oblique angle in order to prevent the reflected ultrasonic wave from arriving at the **ultrasonic transducer** with a phase which is constant all over the **ultrasonic transducer** surface [10].

5.9 Transducer coupling

For precision measurements, the **ultrasonic transducer** should be coupled directly to the measurement liquid in order to avoid an impedance transformation by an additional coupling foil. This is particularly important for very sensitive high accuracy balances in which the ultrasonic beam is directed vertically upwards [11], [12] (Figure 1 and Figure 3). Avoiding the impedance transformation caused by the addition of a coupling foil is particularly important in measurements on high-Q **ultrasonic transducers**.

NOTE An air-backed **ultrasonic transducer**, for example, can be strongly affected by surface pressure.

Detailed technical drawings of a proven device for convenient measurements with a coupling membrane are given in [13]. 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 effectiveness is independently verified.

5.10 Calibration

The **radiation force** balance shall be calibrated by the use of small weights of known mass. Also, the **radiation force** balance should be calibrated by use of an **ultrasonic transducer** of known output power. 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.

6 Requirements for measuring conditions

6.1 Lateral transducer 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 power as well as on the kind of suspension used for the **target**.

6.2 Transducer/Target separation

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

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 of at least 30 mm from the face of the **ultrasonic transducer** [14], depending on the individual details of the situation. This may lead to errors in measurements in the case of a divergent field structure.

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.

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, in order 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**.

Degassing of water shall be accomplished by boiling it for 15 min at atmospheric pressure, or by subjecting it to a reduced pressure of not more than 4 kPa for more than 3 h. Degassing shall be carried out at least once within the 12 h period preceding each measurement series unless special storage methods are used (see IEC 150).

6.4 Water contact

A perfect wetting (water contact) of the **ultrasonic transducer** surface, **target**, and foil should be achieved by storing these parts for at least several hours in degassed water before the measurements are undertaken. Before starting the measurements, care shall be taken to ensure that all air bubbles are removed from the active faces.

NOTE A small drift in the apparent weight of an absorbing **target** may occur during several hours after the beginning of the water storage, due to water resorption of the absorbing material.

6.5 Environmental conditions

For measurements in the milliwatt and microwatt region the measuring device shall be provided with thermal isolation and protected against environmental vibrations and air flow.

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

6.6 Thermal drifts

For an absorbing **target**, in order to be able to estimate the thermal effects due to the absorbed sound energy (expansion and buoyancy change), a recording of the measured signal before and after the switch-on and switch-off of the **ultrasonic transducer** is necessary, and the use of an electronic balance is highly recommended in this case.

7 Measurement uncertainty

7.1 Assessment of measurement uncertainties

Due to the great variety of measurement arrangements used, an uncertainty analysis valid for all possible arrangements is not immediately possible. Therefore, 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.

7.1.1 *Balance system including target suspension*

As a rule, prior to the measurement, the balance system shall be checked or calibrated using small weights of known mass. It is important that this be done with the whole system prepared for radiation force measurements, i.e., with the **target** suspended in water. Thus, any potential influence of the suspension wire penetrating the water surface is automatically taken into account.

This procedure shall be repeated several times with each weight in order to obtain an indication of the random scatter of results. An uncertainty estimate for the balance calibration factor can 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.

7.1.2 *Linearity of the balance system*

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

The measurements described in **7.1.1** shall be done 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 in a graph in accordance with Figure 5. The resulting points in 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 these.

Since weights of less than 10 mg are difficult to handle, the balance linearity check can also be done 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 5 is the ultrasonic **output power** of the transducer.

7.1.3 *Extrapolation to the moment of switching the ultrasonic transducer*

In the case of an electronic balance, in order to obtain the **radiation force** value, the balance output signal is usually 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 can be estimated by means of standard mathematical procedures in utilizing the regression algorithm.

7.1.4 *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** (see Figure 1) 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 1 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 a hydrophone and integrating the square of the measured pressure over the reflected field (see IEC 61101). 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 [10]. This interference effect can be minimised 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 [10]. The uncertainty due to any residual interference effects can be assessed from the oscillation amplitudes.

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 Figure 3) 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.

7.1.5 *Reflecting target geometry*

As discussed in **A.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 $\theta = 27°$, following the notation given in **A.2**) lies within 63° ± 1°, the resulting power uncertainty is ± 1,8 %.

7.1.6 *Lateral absorbers in the case of reflecting target measurements*

Imperfections of the lateral absorbers in the arrangement of Figure 3 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 **7.1.4**).

7.1.7 *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 **A.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.

7.1.8 *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 [32], which appears to be realistic for an alignment by eye.

7.1.9 *Water temperature*

As a result of the temperature dependence of the velocity of sound in water, an uncertainty in the temperature measurement of ± 1 °C will result in a power measurement uncertainty of ± 0.2 %.

7.1.10 *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 below.

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 **A.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 [33] 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 [9]. 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 [17]. This uncertainty contribution depends on the **target** distance and is particularly critical when the measurements are performed in the higher megahertz frequency range.