INTERNATIONAL STANDARD

IEC 61828

First edition
2001-05

Ultrasonics – Focusing transducers – Definitions and measurement methods for the transmitted fields

Ultrasons – Transducteurs focaliseurs – Définitions et méthodes de mesure des champs transmis

Reference number
IEC 61828:2001(E)

Publication numbering

As from 1 January 1997 all IEC publications are issued with a designation in the 60000 series. For example, IEC 34-1 is now referred to as IEC 60034-1.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ULTRASONICS – FOCUSING TRANSDUCERS – DEFINITIONS AND MEASUREMENT METHODS FOR THE TRANSMITTED FIELDS

FOREWORD

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International Standard IEC 61828 has been prepared by IEC technical committee 87: Ultrasonics.

The text of this standard is based on the following documents:

FDIS	Report on voting
87/196/FDIS	87/204/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

Annexes A, B and C are for information only.

The committee has decided that the contents of this publication will remain unchanged until 2005. At this date, the publication will be

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- withdrawn;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

INTRODUCTION

Focusing transducers are essential in medical applications for obtaining high-resolution images, Doppler and flow data and for concentrating ultrasonic energy at desired sites for therapy. Present terminology for focusing transducers is inadequate for communicating precisely the characteristics of the focused fields of the wide variety of transducers and transducer array types and focusing means in common usage.

This International Standard provides specific definitions appropriate for describing the focused field from a theoretical viewpoint for transducers with known characteristics intended by design. Other specific definitions included in this standard, based on measurement methods, provide a means of determining focusing properties, if any, of a transducer of unknown field characteristics. The measurement method and definitions provide criteria for determining if the transducer is focusing, as well as a means of describing the focusing properties of the field. Beam axis alignment methods are given for focusing transducers.

ULTRASONICS – FOCUSING TRANSDUCERS – DEFINITIONS AND MEASUREMENT METHODS FOR THE TRANSMITTED FIELDS

1 Scope

This International Standard

- provides definitions for the transmitted field characteristics of focusing transducers for applications in medical ultrasound;
- relates these definitions to theoretical descriptions, design, and measurement of the transmitted fields of focusing transducers;
- gives measurement methods for obtaining defined characteristics of focusing transducers;
- specifies beam axis alignment methods appropriate for focusing transducers.

This International Standard relates to focusing ultrasonic transducers operating in the frequency range appropriate to medical ultrasound (0,5 MHz to 40 MHz) for both therapeutic and diagnostic applications. It shows how the characteristics of the transmitted field of transducers may be described from the point of view of design, as well as measured by someone with no prior knowledge of the construction details of a particular device. The radiated ultrasound field for a specified excitation is measured by a hydrophone in either a standard test medium (for example, water) or in a given medium. The standard applies only to media where the field behaviour is essentially like that in a fluid (i.e. where the influence of shear waves and elastic anisotropy is small), including soft tissues and tissue-mimicking gels. Any aspects of the field that affect their theoretical description or are important in design are also included. These definitions would have use in scientific communications, system design and description of the performance and safety of systems using these devices.

This standard incorporates definitions from other related standards[1] where possible, and supplies new, more specific terminology, both for defining focusing characteristics and for providing a basis for measurement of these characteristics.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However 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. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

IEC 60050(801):1994, *International Electrotechnical Vocabulary (IEV) – Chapter 801: Acoustics and electroacoustics*

IEC 61102:1991, *Measurement and characterization of ultrasonic fields using hydrophones in the frequency range 0,5 MHz to 15 MHz*

[1] Specifically, IEC 61102 and IEC 61157 (see clause 2).

IEC 61157:1992, *Requirements for the declaration of the acoustic output of medical diagnostic ultrasonic equipment*

IEC 61689:1996, *Ultrasonics – Physiotherapy systems – Performance requirements and methods of measurement in the frequency range 0,5 MHz to 5 MHz*

3 General

The information contained in this clause is an introduction to the definitions given in clause 4 and the measurement methods given in clause 6.

3.1 Focusing transducers

The term "**focusing transducer**"[2] is commonly used for a device which has a smaller beamwidth in some regions of the field than a device which is "non-focusing". A "**non-focusing transducer**" can still have a **natural focus**, so it is necessary to distinguish a **focusing transducer** as having a greater concentration of pressure amplitude (for a given power output) than a **non-focusing transducer** at its **natural focus**. For example, a **non-focusing transducer** made of a simple disc of uniformly poled piezoelectric material has a beam whose intensity at its **natural focus** can be as much as four times the average intensity at the source, and whose –6 dB **beamwidth** can be approximately half of that at the source. A definition of a **focusing transducer** is given in 4.2.33 to make a quantitative distinction between **focusing** and **non-focusing transducers.**

3.1.1 Focusing methods

The simplest means of intentionally focusing an **ultrasonic transducer**, borrowed from analogous optical principles, is that of shaping the **ultrasonic transducer** into a concave form or adding to it a physical lens as illustrated in figure 1. In the top part of this figure, a transducer curved with a radius *R* is shown focusing to the centre of curvature, where *R* is positive by convention. By the geometrical-optics approximation, the focal length *F* is equal to *R* and hence is also positive. In the middle of figure 1 is shown a transducer with a plano-concave lens made of a material with longitudinal velocity, c_L, which is curved on one side with a radius, R_{LENS}, and radiates into a medium in which the velocity is c_W. In acoustics, c_W is typically less than c_L, i.e., the index of refraction *n* (equal to c_W/c_L) is less than 1. When this is true, the radius is considered to be negative and the focal length, given by the geometric-acoustics approximation as R_{LENS} divided by $(n – 1)$, is positive. At the bottom of the figure, for comparison, the typical situation for a convex lens in optics is shown: *n* is greater than 1 and the radius is considered to be positive, so the focal length is positive.

3.1.2 Known and unknown focusing transducers

For **ultrasonic transducers** currently used in medical ultrasound applications, it is difficult to determine from physical observation if an **ultrasonic transducer** is focusing, because additionally many other focusing methods such as geometric shaping and arrangement, reflectors, arrays with electronic phasing and delay, Fresnel lenses, shading, etc. may be used singly or in combination. Because of inherent natural focusing and the potential complexity of additional focusing means used, any generally useful definition of a focusing transducer must be in terms of its field rather than its construction. If a focusing source were to be defined in terms of its pressure field, then this would be relatively easy to apply in practice, since the pressure can be measured directly with a hydrophone.

[2] Terms in bold print are defined in clause 4.

A distinction is also made between **ultrasonic transducers** whose construction is known and transducers about which very little information is available. For the first category of **ultrasonic transducers,** certain theoretical definitions, such as **geometric focal length**, are useful for describing and modelling focusing characteristics. **Ultrasonic transducers** falling in the second category function as an unknown "black box" and only the field may be accessible.

In the latter case, and in general, focusing parameters are determined from measurements, and the measurement procedures of clause 6 are appropriate. In clause 6, measurement methods are given for determining if a transducer system radiating into known propagation media under specified excitation conditions is "focusing". Because of the lack of knowledge of ultrasonic transducer construction and limited access to the **ultrasonic transducer** field, the focusing definitions shown in figure 2 are required. These definitions are given in clause 4 and their use is explained in 3.1.5.

3.1.3 Focusing and beamwidth

Previously, hydrophone measurements of beam characteristics were based on regions of axial peak pressure. For example, definitions for a **depth-of-field** were based on the fall-off in intensity on either the near side or the far side of an axial peak on the **beam axis**. For axially symmetric beams, this axial peak can be related to the **geometric focal length**. For typical rectangular arrays, azimuthal plane electronic focusing and elevational plane mechanical lens focusing can cause peaks of axial pressure at different locations along a **beam axis**. These individual peaks can be dealt with separately by **beamwidth** measurements made in the corresponding orthogonal planes: therefore, new definitions are based on **beamwidths** in a specified **longitudinal plane** (refer to figure 7). Focusing definitions must also distinguish between natural and intentional focusing.

3.1.4 New focusing parameter definitions

This document introduces new focusing parameters and provides more specific contexts for existing terminology. For example, the terms "**near field**" and "**far field**" are often misapplied to **focusing transducers**, though they have traditionally been defined for **non-focusing transducers** only. The definitions **near Fresnel zone**, **far Fresnel zone** and **focal Fraunhofer zone**, apply to **focusing transducers**. These definitions, explained in more detail in 3.3 and derived from annex A, are illustrated in figure 3b and are applied to a strongly focusing circular aperture in figure 4. Other concepts such as focusing in a particular plane are also necessary to reduce ambiguity in usage.

For the purposes of this document, the following definitions for a **focusing transducer** will be used.

For **ultrasonic transducers** of known construction (refer to figure 5 for transducer geometry and terms), a **focusing transducer** is an electro-acoustic device that produces, at any distance less than one-half of the **transition distance** from the **transducer aperture,** a –6 dB **beamwidth** in a **longitudinal plane** that is less than half the **transducer aperture width** in that plane. For measurement purposes and cases (see figure 2) where the geometry of the **ultrasonic transducer** is not known or where there is no direct access to the **ultrasonic transducer** (because of the device being used in some stand-off arrangement), a definition of focusing based on data is more appropriate. For this second case, a **focusing transducer** is an electro-acoustic device that produces, at any distance less than half of the **transition distance** from the **source aperture,** a –6 dB **beamwidth** in a **longitudinal plane** that is less than one-half the –20 dB **source aperture width** (measured in a plane as close as possible to the **ultrasonic transducer**) in that plane. For arrays with a rectangular geometry, a specified **longitudinal plane** is either an *xz* or *yz* plane with *z* along the **beam axis**. **Non-focusing transducers** are those not meeting the conditions specified above.

3.1.5 Applications of focusing definitions

Two definitions of focusing are given in 3.1.4, which apply in two cases.

a) For transducers for which the construction is known, an ideal definition is given for describing, modeling or design purposes.

b) A second definition applies to measurements of the focusing characteristics of real transducers which either have an unknown construction or imperfect realization.

Use of the first definition is not a substitute for actual measurement. Whether or not a transducer is focusing in practice must be determined by the second definition for transducers of unknown construction and by the measurement procedures of clause 6. Knowledge about the transducer (first definition) may be helpful in guiding measurements. If measurements meet the criteria of the second definition, the transducer is focusing, irrespective of whether focusing was intentional or accidental.

3.1.6 Relation of present definitions to physiotherapy transducers (treatment heads)

The definition of focusing in the present document is not related to the definitions of "divergent, collimated and convergent" beams as described in IEC 61689. The definition of beam type is based on energy and area considerations that are more important for physiotherapy transducers. The definition of focusing in the present document is based on a different parameter: –6 dB beamwidth. This definition is useful in identifying the existence and location of the highest field concentrations. When the current document is applied to physiotherapy transducers, focusing can be understood to correspond to high-beam non-uniformity ratio "hot-spot" transducers.

3.2 System and measurement requirements

In 3.1 it was shown that the radiating device has to be considered as a whole, because it is not possible to define a **focusing transducer** in terms of the properties of its component elements**.** For clinical ultrasound systems, each of the measured focusing definitions only applies for the field of a selected **scan line** generated by given electrical excitation conditions and for a given medium.

3.2.1 Transmitted pressure waveforms

Because a wide variety of transmitted pressure waveforms are possible in an **ultrasonic transducer** field, a measure of these waveforms must be robust enough to accommodate broad-band or narrowband pulses, **continuous-wave signals** or even waveforms distorted by non-linear propagation. For this reason, the **pulse-pressure-squared-integral** (see 3.33 of IEC 61102) will be the field measurement used throughout this document. For certain types of waveforms under the conditions of linear propagation, the **pulse-pressure-squared-integral** can be related to more familiar pressure terminology. For example, for linear, **continuous-wave signals**, the **pulse-pressure-squared-integral** divided by the period of one cycle is the root-mean-square acoustic pressure squared. In other cases, when ratios of these integrals are involved, these ratios can be thought of as ratios of equivalent squared pressures. In such cases, ratios of the square roots of the **pulse-pressure-squared-integral** are analogous to ratios of equivalent pressures.

3.2.2 Radiated fields

The radiated field of an **ultrasonic transducer** is dependent on the bandwidth of the **ultrasonic transducer** as well as the type of excitation used. Frequently used models for beam simulation such as that described in annex A are appropriate only for continuous-wave excitation. For simulating the pulsed excitation of an **ultrasonic transducer**, the driving waveform and the impulse response of the **ultrasonic transducer** element as well as the boundary conditions need to be considered. As the bandwidth of a pressure **acoustic pulse waveform** launched by an element increases, the resulting field becomes smoother compared to a field from a **continuous-wave signal**.

In addition to the field depending on the waveform of the electrical driving function and the propagation medium, it will also depend on the amplitude of the electrical input. This feature is due to non-linear propagation, which is frequently present in the type of field being considered. A parameter called the **non-linear propagation parameter** (3.25 of IEC 61102) has been previously defined and, in general, the assumption of linearity can be made provided that this parameter is less than approximately 0,2.

3.3 General focused field descriptions

New terms for describing the transmitted focused field of an **ultrasonic transducer** of known construction are introduced in 4.2. Refer to figure 1, which shows the primary geometrical relationships for the definitions. Background information for these definitions can be found in annex A.

Measured focusing definitions, also in 4.2, can be used to characterize the focusing acoustic field of an unknown acoustic source through measurements. In this case a measurement plane, the **source aperture plane**, is chosen as close as possible to the source. An equivalent acoustic aperture, the **source aperture** on this plane, is used for determining the effective focusing characteristics of the field. As with the focusing definitions for an ultrasonic **transducer** of known design, the **ultrasonic transducer** is considered as an ultrasonic transducer system with a specified set of operating conditions and medium of propagation and **offset distance**. Conditions of acoustic linearity are desirable but not necessary for these measurements, and the **non-linear propagation parameter** must be specified. Figure 2 shows the relationship among several of these measurement definitions.

3.3.1 General field descriptions for transducers of known construction

From the fields of focusing transducers of known construction, it is possible to determine general characteristics of focused fields. Ultrasound focusing is not well described by geometric optics because of beam diffraction resulting from transducer sizes on the order of wavelengths. Natural focusing of the beam is combined with the focusing of a lens or other focusing device. The resulting combined effect is that the narrowest **–6 dB beamwidth** does not in general occur at the **geometric focal length** of the focusing device, but approximately at a distance

$$z_{\min} = \frac{z_T \; F}{z_T + F} \qquad (1)$$

where

z_T is the transition distance, the natural focal length;

F is the **geometric focal length** (as explained in annex A, equation (A.11c)).

This equation shows that the distance to the location of the minimum **beamwidth** cannot exceed the **transition distance** even when the **geometric focal length** is greater than the **transition distance**.

An approximate relation exists between the characteristics of focused fields and non-focused fields. In a **longitudinal plane**, beam profiles at an axial distance z in a focused field are similar in shape to a beam profile in a non-focused field occurring at an equivalent depth, z_e (see annex A for the approximations used in the derivation of equation (A.8)),

$$z_e = \frac{z}{\left|1 - \dfrac{z}{F}\right|} \qquad \text{(valid for } z \neq F\text{, and } F \text{ positive)} \qquad (2)$$

This equation indicates that to a good approximation, the field of a **focusing transducer** (within a **longitudinal plane**) takes on all of the **near-field** and **far-field** beam profile shapes of a **non-focusing transducer** of the same size in the distance between the **ultrasonic transducer** and the **geometric focus**. At the **geometric focus**, the equivalent distance becomes infinite and equation (2) no longer holds: the shape of the beam profile is the same as that obtained in the **far field** of an identically sized **non-focusing transducer**. The evolution of the field of a **focusing transducer** is accelerated by the scaling of equation (2) compared to the field of a **non-focusing transducer**, and the transverse width of the beam becomes narrower than that of a **non-focusing transducer** at distances close to the geometric focus.

In a manner consistent with the determination of the **transition distance**, the distance separating the **near field** and **far field** of a **non-focusing transducer**, transition distances can be found for similar descriptions of a focused field. The focused field can be divided into three regions, the **near Fresnel zone,** the **focal Franhofer zone** and the **far Fresnel zone,** as shown in figure 3b. The corresponding distances separating these zones are the **near transition distance**, z_{NTD},

$$\frac{1}{z_{NTD}} = \frac{1}{z_T} + \frac{1}{F} \qquad (3)$$

and the **far transition distance**, z_{FTD},

$$\frac{1}{z_{FTD}} = -\frac{1}{z_T} + \frac{1}{F} \qquad (4)$$

More information about these distances can be found in annex A (equation (A.11)).

3.3.2 The scan plane and the steering of beams

In addition to being focused, beams can also be made to change direction. This direction corresponds to a **scan line**, the **beam axis** for a particular **ultrasonic transducer element group**. The **scan plane** (or surface) is the plane or surface containing all the ultrasonic **scan lines**. The **scan plane** is also known as the **azimuth plane**. For most cases, the elevation plane is orthogonal to the azimuth plane and contains the central **scan line** – the beam direction corresponding to an undeflected or unsteered beam.

The pattern of **scan lines** depends on the image format, the geometry of the **ultrasonic transducer** and the method of transducer excitation. Several examples of scanning are described below: sector (angular), linear (translation), and two-dimensional arrays.

Sector (angular) scanning is accomplished by either mechanically sweeping a single transducer in an arc or by changing the electronic excitation of active transducer elements, an **ultrasonic transducer element group,** to produce angular deflections of the beam. The resulting pattern of **scan lines** has a fan-like appearance and results in a sector image format.

An **unsteered beam** is one selected to be in the forward propagation direction without angular deflection. The direction of this beam corresponds to the central scan line of a sector scan. For the usual case in which the **ultrasonic transducer** is symmetric, the **unsteered beam** may be chosen to be near the symmetry axis or a symmetry plane of the **ultrasonic transducer**.

Linear scanning is the translation of active transducer elements, an **ultrasonic transducer element group,** along the array surface (or by mechanically translating a single transducer).

When the array is flat and linear, a pattern of parallel **scan lines** forms a rectangular image format. When a curved linear array geometry is used, the translation of the **ultrasonic transducer element groups** results in **scan lines** which have an angular separation and result in a sector type image format. In this case, angular deflection is caused by the transducer geometry and not electronic steering.

In the most general case, a combination of methods for steering and focusing the beam simultaneously may be used. In the situations described above, a mechanical lens with a fixed focal length is applied to focus in the **elevation plane**. For a two-dimensional array, the **scan plane** is not simply related to the shape or geometry of the array. Azimuth and elevation focusing are coincident. Diagonal segments of the array or all elements of the array can be employed to steer and focus the beam simultaneously at an arbitrary angle to the transducer aperture. In the most common method used to form a three-dimensional image, the array sweeps through a series of planes to fill a volume to be imaged. In this case, the position of each **scan plane** is time-dependent, and by definition there is a corresponding orthogonal **elevation plane**. Just as there is a central scan line in a **scan plane**, a central scan plane can often be identified near the symmetry axis or a symmetry plane of the **ultrasonic transducer**.

4 Focusing definitions

4.1 Background information

Definitions listed below fall into three general categories. The first are those definitions directly applicable to describing and modelling focused fields. The second group of definitions relates to measurements of focused fields. Some of the terms in the second group overlap with those of the first. Third, additional commonly used terms about focusing have been included. Previously used definitions have been modified or made more specific to remove ambiguity in usage. Definitions related to focusing in 4.2 are not grouped but follow an alphabetical order.

4.2 Definitions

For the purposes of this International Standard, the following definitions apply.

4.2.1
acoustic pulse waveform
temporal waveform of the instantaneous acoustic pressure at a specified position in an acoustic field and displayed over a period sufficiently long to include all significant acoustic information in a single pulse, a single tone-burst, or one cycle of a continuous wave

[IEC 61102, definition 3.2]

NOTE In some cases such as an amplitude-modulated pulse, the overall pulse train may appear as a group of nearly contiguous pulses with spacings much smaller than the overall pulse repetition time.

4.2.2
annular array
any **ultrasonic transducer element group** having radiating elements in the same plane or curved surface and consisting of concentric elements which are electrically phased to control the characteristics of an acoustic beam

4.2.3
aperture path difference
difference in path lengths from a specified **geometric focus** to the periphery of the **transducer aperture** and to the intersection of the **beam axis** with the **transducer aperture plane** for a specified **longitudinal plane** and for an **unsteered beam**

(See figure 6 and annex A for details.)

Symbol: Δ
Unit: metre, m