Optimization of Ultrasound Broadband Transducers for Complex Testing Problems by Means of Transient and Time Harmonic Sound Fields

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Abstract. Transducer parameters and measurement setup are usually optimized by means of their simulated time harmonic sound field at center frequency of the broadband transducer. This paper deals with the relation between time harmonic and transient sound field and discusses the question if optimization by the time harmonic field is an appropriate approach. The paper also investigates a variation in the spectrum in dependence on the number of passed layers. This is explored with two examples: “testing of a shrink fit in immersions technique” and “testing of shafts”.

1. Introduction

A harmonic sound field that is emitted into a complex structure (with non-parallel and curved interfaces) can be efficiently calculated by a separation approach in connection with time harmonic GREEN's functions in a steepest descent approximation and a point source synthesis [1,2]. By means of this approach, the time harmonic sound fields are calculated for different inspection problems:

- sound field of angle beam probes in steel [2]
- sound field in human eye [2,3]
- sound field of a focused probe at a press-fit interface in immersion technique [2, 4].

In these examples the probes and/or the measurement setup are optimized. The fitting procedure of the setup is a systematical variation process of the probe parameters and of the measurement setup in simulation. This process lasts until a suitable sound field is reached.

Since the applied transducers are broadband ones, the relation of the transient and the harmonic sound field is examined as a one-dimensional problem (i.e. the emission of a plane element into a solid half space) in [5, 6]. It is shown that the time harmonic sound field for the center frequency of the broadband transducer appropriately predicts the transient field. Therefore, broadband angle-beam probes are optimized by means of simulating time harmonic fields for center frequency [7]. The transient sound field is calculated to determine how far the duration of the excitation signal influences the chosen measurement setup. Thereby, the results of the harmonic simulation are proved. The relation between transient and time harmonic sound fields needs further attention for other complex NDT-problems. This paper hence investigates the sound fields of focused and an unfocussed transducers in test objects with curved interfaces.

2. Theory

The approach for calculating the time harmonic sound field is based on three columns: 1. the time harmonic GREEN’s functions in a steepest descent approximation, 2. a superposition of the fields of all point sources to get the field for the single element transducer and 3. a separate calculation in each layer [1,2].

The time harmonic GREEN’s functions for a two-dimensional geometry (plane interfaces) are integral expressions, which consist of source, receiver and propagation function as well as of generalized reflection or transmission coefficients. Assuming sources on the interface, the source terms contain reflection coefficients and thus the parameters c_{L1}, c_{L2}, c_{T1}, c_{T2} ρ_1, ρ_2 of both media. Thus, reflection, transmission and mode conversion on the interfaces are taken into account. Applying appropriate reflection coefficients may satisfy various boundary conditions. (These GREEN’s functions are compared with the GREEN’s functions of rigid and soft boundary conditions in [11].) The present approach does not numerically evaluate the integral expressions of the GREEN’s functions; instead, a steepest descent approximation is used according to [8]. This results in spherical waves due to propagation terms while the point-source term leads to a directivity pattern. Such an approximation already agrees with an exact calculation in a distance of about one wavelength from the interface. By means of the propagation terms, interference is taken into account.

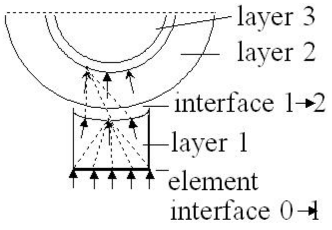


Figure 1. Separation approach

Based on GREEN's functions for a two-dimensional geometry (plane interfaces), the field that is radiated by a wide source into a layered medium with curved interfaces can be calculated approximately by a decomposition of the medium into different layers and a separate wave propagation calculation in each layer (Fig. 1). For this purpose, the transducer element and the interfaces are discretized and uniformly covered by point sources with a distance of $\lambda/7$. The wave field results from the superposition of all elementary waves emitted by the point sources. At the interfaces, the normal stress is calculated for points equally spaced. Afterwards, each point is considered as a new point source. This yields to the time-harmonic sound field in a layered medium with curved interfaces. However, in this approach multiple reflected waves are neglected. This is sufficient as long as the multiple reflected waves are separated in time.

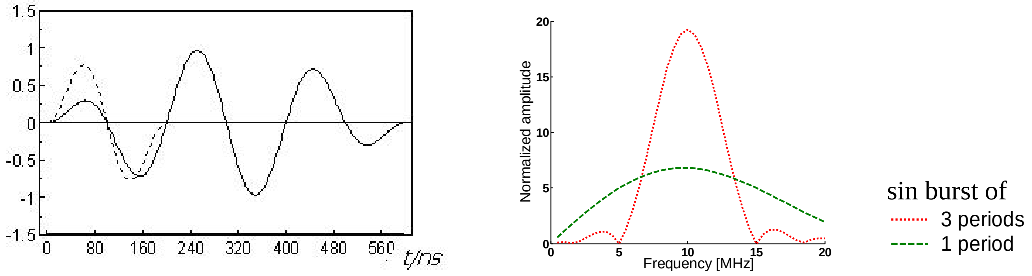


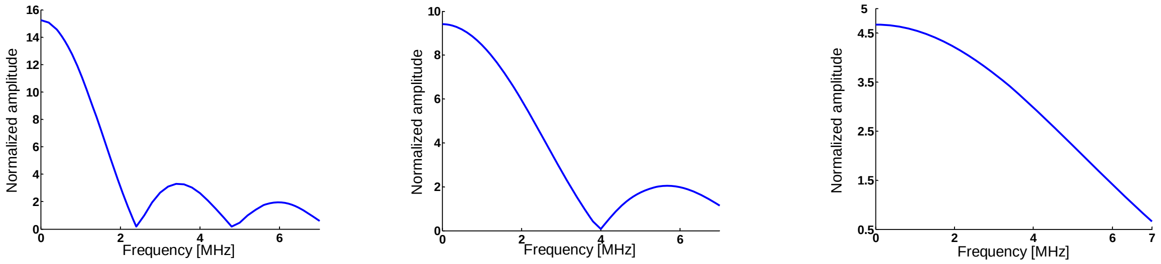
Figure 2. Excitation function

a) time domain

b) frequency domain

The transient sound field is calculated by means of a harmonic synthesis and a temporal convolution with the excitation function [5]. This is done by an optimized approximation method, which is based on a superposition of small number of time harmonic sound fields at selected frequencies. These sound fields are calculated according to the approach above. Calculating the corresponding transient field lasts about 20 times longer than the calculation of the corresponding time harmonic sound field. The optimized approximation method is evaluated by an exact calculation based on transient GREEN's functions in [5, 6]. There, it is shown that the optimized approximation method is in agreement with the exact calculation. In the following examples, a sine burst of n cycles is used as excitation function for different center frequencies (Fig.2).

It has to be noticed that the impulse response of a piston transducer in water is a rectangle with a constant height H_R on axis. The width of rectangle results from the time difference between the arriving longitudinal wave from the middle of the element and the arriving longitudinal edge wave. It becomes smaller with larger distance to the transducer. In the frequency domain, the transfer function results in a sinc-function (Fig.3) with an increasing width B_S and a decreasing height H_S for an increasing distance to the transducer ($B_S\, H_S = H_R$).



a) z=20 mm b) z=33 mm c) z=67 mm

Figure 3. Transfer function of a round element (r=5mm) in water at different distances z from the transducer (one-layered problem) a) z=20 mm, b) z=33 mm, c) z=67 mm

3. Calculation Examples

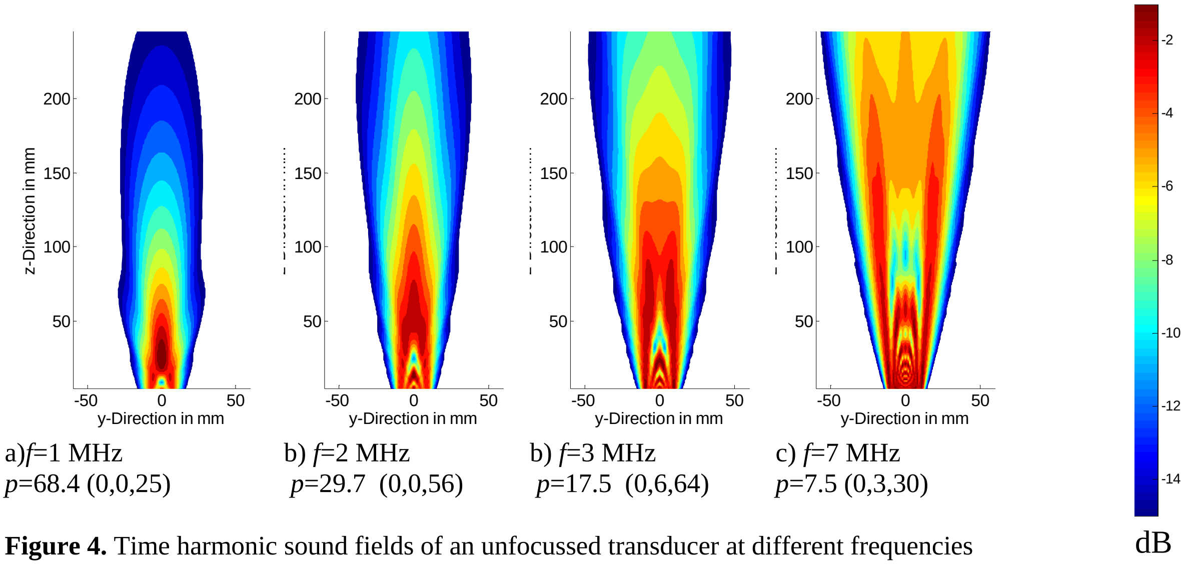
All figures show either the longitudinal sections of the sound field inside a layer (yz-plane) or the cross section (xy-plane) at an interface. The coordinate system is placed on interfaces so that the z-coordinate represents the distance to the latest passed interface. The interface to the next layer is firstly neglected to observe the location of the sensitivity zone and the divergence of the beam within the concerned layer. In selected figures, the normalized maximum p is given including its location. Inside one figure, the given p-values are comparable (in Fig.11 only a to c and d to e).

3.1 Example 1: Optimization of Two-Layered Problems

Example 1 is an unfocussed transducer (element r=12 mm, center frequency f_M=3MHz), which is used for testing steel shafts with r=70mm. Fig. 4 presents time harmonic sound fields emitted by the broadband transducer into the shaft. The comparison of the sound fields at different frequencies reveals that, by increasing frequency, both the sound field becomes more divergent and the sensitive zone shifts away from the probe and splits into parts (see Fig. 4). The transient sound field is a convolution of the impulse response of the system with the excitation function. The transient sound field is calculated by harmonic synthesis that is a superposition of the time harmonic fields according to the time excitation of the input signals.

Fig.5a and 5b show the transient sound fields for the center frequency f_M=3MHz and a time excitation by a windowed sine function lasting 1 and 3 periods, respectively. The transient sound field is highly similar to the harmonic one at the center frequency of the broadband transducer (compare Fig.5a, b with Fig. 4c). The similarities occur mainly in terms of the width of the sound fields as well as in the position and extension of the sensitive zone. The time harmonic sound field at center frequency is a good approximation of the transient sound field, even for 1 period. The time harmonic field also predicts the splitting of the sensitivity zone for longer excitation functions.

The transducer with a center frequency of 3MHz does not suit the particular testing problem since the sound field splits into secondary off-axis structures for higher curvature. This can cause an incorrect testing result. It is possible to improve this setup if the transducer has either a lower center frequency of f_M=2MHz (Fig.5c,d), a smaller element size Fig.6a, a lens or a curved element as in Fig.6b,c. A focused transducer obviously offers the best resolution for immersion technique but is limited to testing near the surface. Yet, a smaller element size or a lower frequency enable us also to test in more distanced areas of the testing object. To demonstrate the difference between focused and unfocussed transducer, Fig.6 also displays the cross section of sound fields in the maximum in the same scale.



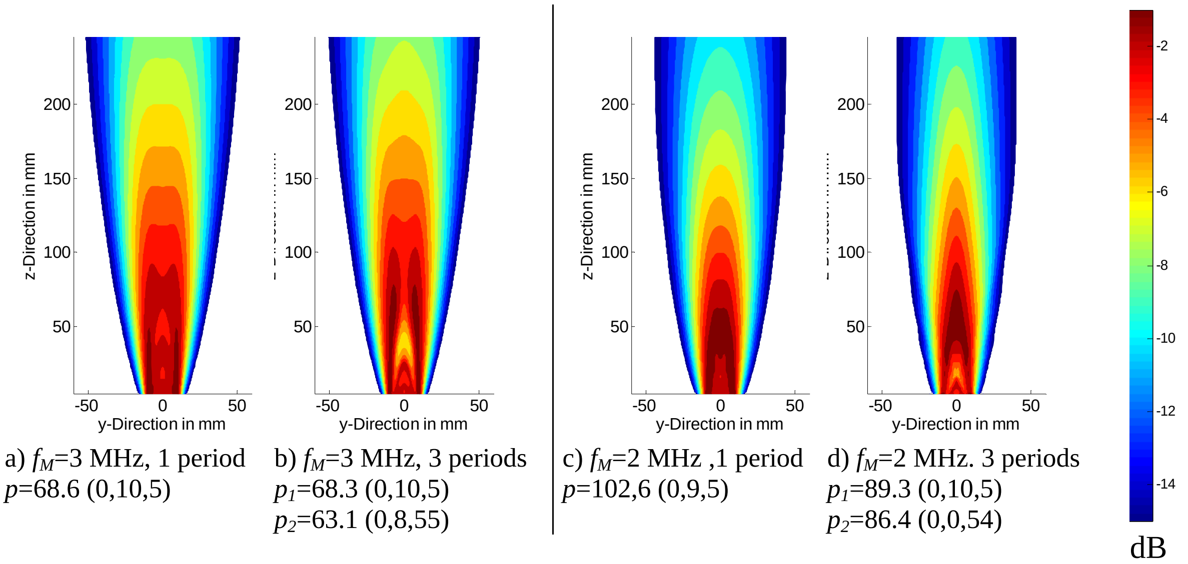
a) f=1 MHz
p=68.4 (0,0,25)

b) f=2 MHz
p=29.7 (0,0,56)

b) f=3 MHz
p=17.5 (0,6,64)

c) f=7 MHz
p=7.5 (0,3,30)

Figure 4. Time harmonic sound fields of an unfocussed transducer at different frequencies in a steel shaft r=70 mm (element r=12mm; Plexiglas delay of 5 mm)



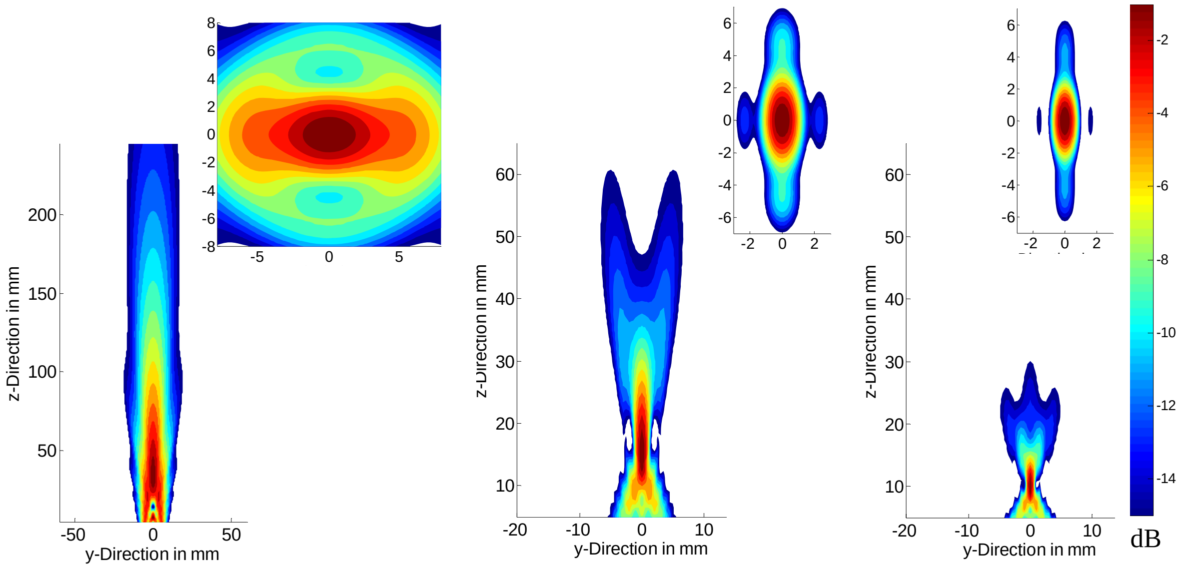
a) f_M=3 MHz, 1 period
p=68.6 (0,10,5)

b) f_M=3 MHz, 3 periods
p_1=68.3 (0,10,5)
p_2=63.1 (0,8,55)

c) f_M=2 MHz ,1 period
p=102,6 (0,9,5)

d) f_M=2 MHz. 3 periods
p_1=89.3 (0,10,5)
p_2=86.4 (0,0,54)

Figure 5. Transient sound fields in a steel shaft r=70 mm (element r=12mm; Plexiglas delay of 5 mm)



a) unfocussed transducer element
d=16mm, f=3MHz
p=23.3 (0,0,34)

b) element: 8mm x 22 mm,
r_f=60mm, f=4MHz
p=29.6 (0,0,15)

c) element:6mm x 22mm,
r_f=40mm, f=4MHz
p=34.4 (0,0,10)

Figure 6. Possible improvements of measurement setup for testing a shaft with r=70 mm
a) unfocussed transducer element d=8mm b) and c) immersions technique with curved foil transducer with curvature r_f, water delay 10mm (normalized p with respect to Fig.4)

3.2 Example 2: Optimization of Multi-Layered Problems - Testing of a Shrink Fit in Immersions Technique

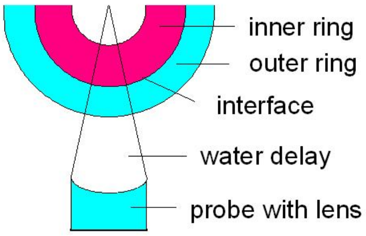
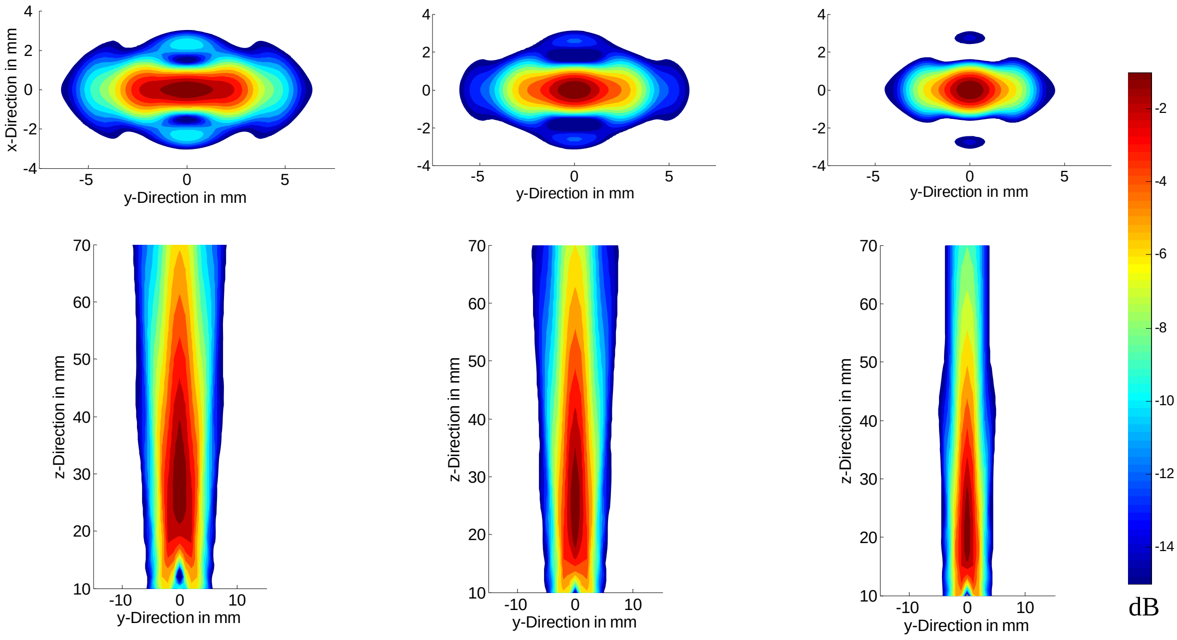


Figure 7. Measurement setup of example 4

The original aim of Example 2 is to select a probe from a given set and to optimize the measurement setup for testing a shrink fit of a two-ring component in immersion (Fig. 8). This is described in more detail in [9]. The example is a four-layered problem: probe with lens, water delay, outer and inner ring. The outer radius of the peripheral ring is r=100mm while that of the inner ring is r=75mm. Fig. 8 shows the longitudinal section of the sound field inside the outer ring (bottom line) and the cross section on the interface between the two rings for different setups (on top). Setup 3 (Fig. 8c) has the smallest sensitive zone on the interface and thus the best lateral resolution. This is confirmed by measurements in [9].

Setup 1 in Fig. 8a is chosen to investigate the relation between transient and harmonic sound field. In this case, the focusing transducer has an element size of d=12.7 mm, a focus in water at 135 mm and a center frequency of f_M=10 MHz. Fig. 9 and 10 present the time harmonic sound fields for various frequency parts and the corresponding transient sound fields on the interface between the rings. Fig. 11 shows time harmonic and transient sound fields inside the outer ring. There is a good agreement between the time harmonic sound field at center frequency and the transient sound fields; the time harmonic sound field at center frequency gives the correct location of the focus. For a short excitation function, the transient sound field is more divergent than the sound field at center frequency.

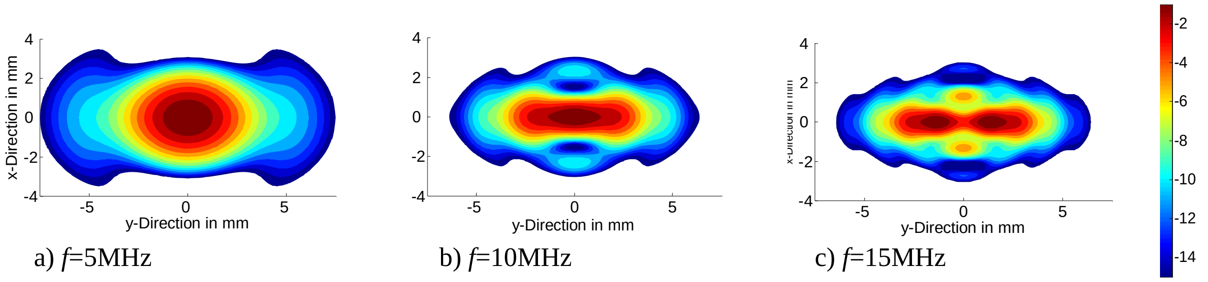


a) setup 1: probe 10 (*d*=12.7mm, *f*=10MHz, focus in water 135mm) by a water delay of 35 mm

b) setup 2: probe 10 (*d*=12.7mm, *f*=10MHz; focus in water 135mm) by a water delay of 45 mm

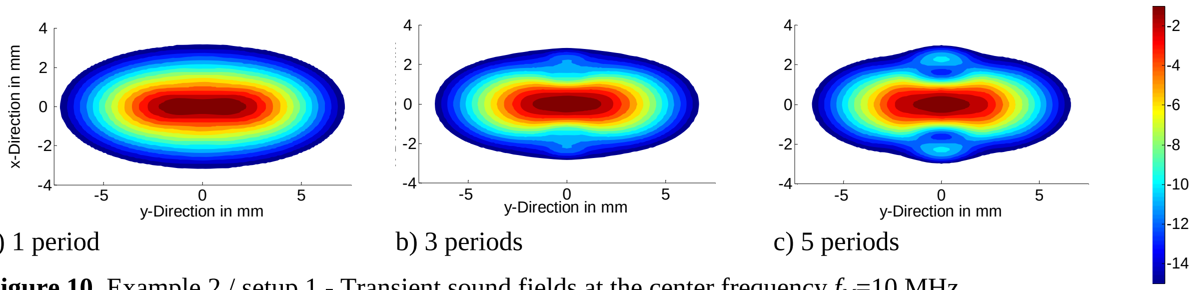
c) setup 3: probe 4 (*d*=12.7mm, *f*=9 MHz; focus in water 81mm) by a water delay of 10 mm

Figure 8. Example 2 - Harmonic sound field of various measurement setups for testing a shrink fit below: inside the outer ring above: on the interface



a) *f*=5MHz b) *f*=10MHz c) *f*=15MHz

Figure 9. Example 2 / setup 1 - Time harmonic sound fields on the interface



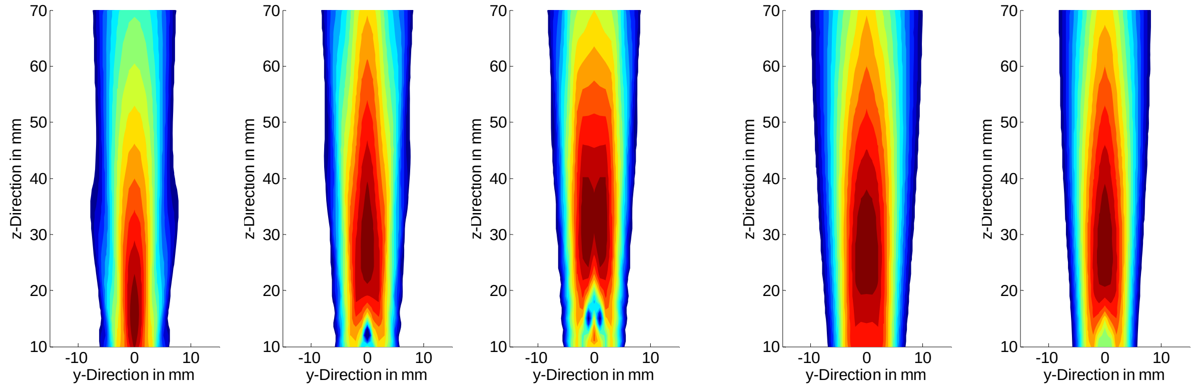
a) 1 period b) 3 periods c) 5 periods

Figure 10. Example 2 / setup 1 - Transient sound fields at the center frequency f_M=10 MHz on the interface for different excitation functions

To investigate a possible alternation within the amplitude spectrum after the transmission through two curved interfaces, Fig.12 shows the transfer function in water delay and inside the outer ring on different positions. The positions in water and steel correspond to each other (Fig.12 a) water delay before steel, b) water at z=75mm with d) steel at 12 mm after a water delay of 35mm, c) maximum in water at 138mm with e) the maximum in steel at 28mm). Caused by the curved lens, the sound field in water delay already differs from a sinc function (compare Fig.12 above with Fig.3). Inside the outer ring (third layer), the difference increases. Especially, the higher frequencies are damped stronger than the lower frequencies. (Compare firstly the second local maximum of curve 12b and 12d; secondly the faster decrease of the transfer function in Fig.12e in comparison to Fig.12c) Hence, there is an additional attenuation of higher frequencies after transmission to several interfaces in comparison to the sinc function. Of course, the zeros of the transfer function only depend on the location within the field.

Fig.12 also shows the results of the spectral multiplication of the impulse response and the excitation function. For a short excitation signal, the maximum can occur at a different frequency than the center frequency of the excitation signal. This effects more extremely, if the transfer function differs significantly from the sinc function (compare Fig. 12c and 12e – green dashed lines). The location shift of the maximum of the spectrum causes a decreased resolution. However, this effect does not matter as strongly as expected in [10].

Harmonic sound field at different frequencies **Transient: f_M=10 MHz**



a) f=5MHz p=25.8 (0,0,14)

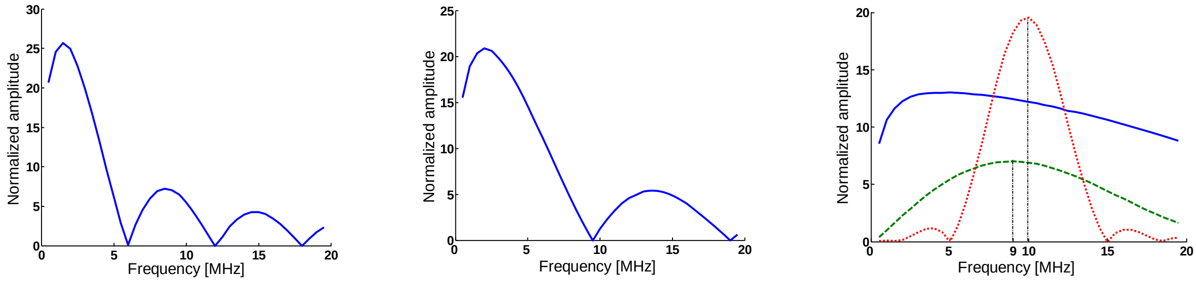
b) f=10MHz p=14.5 (0,0,28)

c) f=15MHz p=10.4 (0,1.30)

a) 1 period p=10.4 (0,0,28)

b) 3 periods p=14.2 (0,0,28)

Figure 11. Example 2 / setup 1 - Time harmonic and transient sound fields inside the outer ring

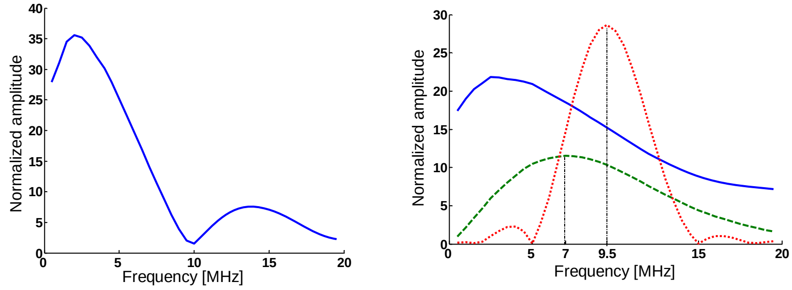


a) water z=55 mm

b) water z=75 mm

c) water z=138.5 mm –at focus

1. —— impulse response
2. spectral multiplication between impulse response and excitation function
   - - - - excitation function 1 period
   ········ excitation function 3 periods



d) steel z=12 mm

e) steel z=28 mm

Figure 12. Transfer function of setup 3 in water and steel at corresponding position

4. Conclusion

To conclude, the harmonic sound field at center frequency is a good approximation of the transient sound field, even for short signals. The similarities mainly occur both in the width of the sound fields and in the position and extension of the sensitive zone. The harmonic sound field predicts the eventually appearing secondary structures for longer excitations. Thus, the discussed approach by means of time harmonic sound field is an efficient tool to optimize transducer parameters and measurement setup for broadband transducers.

The paper also discusses the transfer function at particular points in water layer and in steel. It is shown that the lens of the focused transducer already caused a transfer function that differs from the sinc function of a piston probe. Additionally, interfaces also change the transfer function. Thus for a short excitation signal, the maximum of transfer function can occur at a lower frequency than the center frequency of the excitation signal. This causes a decrease in the lateral resolution.

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