IMPROVING ULTRASONIC BEAM CHARACTERISTICS FROM SEGMENTED ANNULAR ARRAYS

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Oscar Martínez[1], Gregorio Godoy[2], Luis G. Ullate[1]

[1] Instituto de Automática Industrial (CSIC)
La Poveda, Arganda del Rey, 28500, Madrid
e-mail: oscarm@iai.csic.es and luisg@iai.csic.es

[2] Departamento de Electrónica - Universidad de Jaén
Alfonso X El Sabio, 28, Edificio 71, 23700 Linares, Jaén
e-mail: ggodoy@ujaen.es

ABSTRACT

Segmented annular arrays are useful for volumetric imaging because they allow a reduction of the amount of array elements. High quality imaging requires good characteristics of resolution, low side lobes and large depth of focus. In this sense, changing electronically the focussing lens and/or apodization function of the transducer the image quality can be modified. An analysis of the beam radiated by segmented annular arrays of size is presented in this paper. Several lens profiles are compared to the case of dynamic focussing, which is considered as gold standard. The influence of apodization over the beam characteristics is also shown in the paper.

INTRODUCTION

Several methods are studied to improve the beam characteristics of 2D segmented annular (SA) arrays. SA arrays are useful because reduce grating lobes in volumetric imaging, allowing a reduction of the amount of array elements [1].

High quality imaging requires good characteristics of resolution, low side lobes and large depth of focus, among others. In this sense, transducer arrays permit modifying electronically both the focusing law and the apodization function with the object of improving the ultrasonic beam properties. Conventionally, dynamic focusing is used in reception to improve the lateral resolution and image contrast at all the depth range. However, transducer arrays can be focused only at one point in transmission. In this case, Gaussian or cosine apodization functions are employed to increase the depth of field. Axicons (in acoustics, axicons are typically conical and toroidal transducers) have also been used to obtain beams of large depth of field.

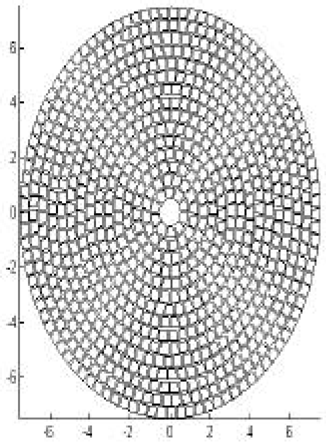

Figure 1. 2D segmented annular array (SA1) of diameter equal to 30λ. It is composed by 800 elements with unitary aspect ratio (0.84λ*0.84λ of size), which are distributed in 15 rings. The inter-element spacing is d=λ.

In the last ten years, non-diffracting beams have attracted much attention as they maintain a narrow and uniform profile during a very long distance in the propagation direction. Durnin proposed in 1987 the Bessel beam [2], which is based on a non-diffracting solution to the wave equation. For continuous wave radiation, a Bessel type beam is very similar in concept to an axicon having comparable expressions for the beamwidth and for the depth of field. But the width of the Bessel beam is dependent on the frequency, and for broadband operation it is equivalent to a conical beam with frequency dependent cone angle. Non-diffracting beams for wide band pulses have been presented by Campbell [3] and Lu [4,5], who called them X waves. In both cases, the waves propagate without changing their waveforms in both space and time.

Non diffracting beams are usually based on annular transducers of large size (D>60λ) with radiation normal to the aperture plane [6,7]. The feasibility of steering these beams with a 2D array has been studied in Ref. [8]. In this work, a 2D array (D=60λ) with thousands of squared elements is used and it is concluded that the reduction of the array effective area with steering has a negative impact on the production of limited diffraction beams. A compensation of this area reduction is proposed, but that solution implies a further increase of the array elements and of the electronic complexity. For these reasons, it seems not advisable to use non-diffracting beams in the case of volumetric phase scanning and simplified solutions to improve the beam characteristics should be employed. In this sense, Yamada proposes weighted conical transducers able to create a sound field closed to the Bessel beam [9]. Solutions of this type are studied in this work for the case of segmented annular (SA) arrays.

SIMULATIONS

A SA array (SA1) with diameter of 30λ in one way has been considered. The array has 800 elements with unitary aspect ratio (0.84λ*0.84λ of size) (Figure 1), which are distributed in 15 rings. The inter-element spacing is d=λ. The SA array radiates waves into water with 3MHz of central frequency and 50% of relative bandwidth. The wavelength is then λ=0.5mm. The computational method used in simulations has been presented in Ref. ??.

Simulations are made for the following array configurations:

1. Full array with dynamical focusing (this is considered the optimal)
2. Full array with spherical focusing at $F(r^F = 56mm, \theta^F = 30^o)$.
3. Full array with conical focusing at F. The cone angle α is given by: $tg\alpha = D\cos\theta^F / 4r^F$
4. Full array with toroidal focusing at F of inverse curvature than the spherical lens
5. The three outer array rings and single steering an angle θ^F.

A paraxial approximation of the focusing delays for the i^th element is then:

$$
\begin{aligned}
T^{CON}(i) &= T^{\theta}(i) + T^{\alpha}(i) \\
T^{SPH}(i) &= T^{\theta}(i) + T^{\alpha}(i) + T^{PX}(i) \\
T^{TOR}(i) &= T^{\theta}(i) + T^{\alpha}(i) - T^{PX}(i)
\end{aligned}
\qquad [1]
$$

where $T^{CON}(i)$, $T^{SPH}(i)$ and $T^{TOR}(i)$ respectively are the delays for conical, spherical and toroidal focussing. $T^{\theta}(i)$ is the steering term, $T^{\alpha}(i)$ is the conical term and $T^{PX}(i)$ is the paraxial approximation of the spherical term of the delay (Figure 2).

$$
\begin{aligned}
T^{\theta}(i) &= (x_i \cos\phi^F + y_i \sin\phi^F)\sin\theta^F / c \\
T^{\alpha}(i) &= \tan\alpha\sqrt{x_i^2 + y_i^2} / c \\
T^{PX}(i) &= \left(\sqrt{x_i^2 + y_i^2} - D/4\right)^2 \cos\theta^F \Big/ 2cr^F
\end{aligned}
\qquad [2]
$$

The effect of apodization will be studied comparing the cosine and uniform apodization functions, besides other particular functions to obtain beams close to non-diffracting.

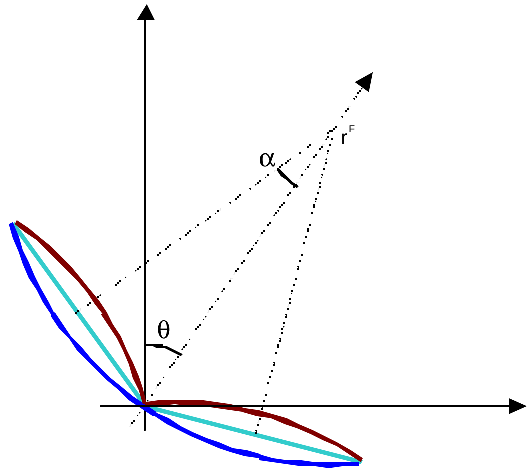

Figure 2 Geometry of the conical (green), spherical (blue) and toroidal (brown) focussing profiles.
r^F is the depth of focus, θ is the steering angle.

UNIFORM APODISATION

Figure 3-a shows the pressure axial profile for the five array configurations steering the beam 30º in elevation. In Table I, parameters describing the beam quality are evaluated: (a) the axial intensity measured as the integral of the pressure amplitude along the axial profile in the depth range $r^F/2<r<2r^F$ (this parameter is given in dB with respect dynamic focusing with uniform apodisation); (b) the depth of focus (DF) at the -3dB cutting level and (c) the beam width (BW) at -6dB and -20 dB cutting levels and the grating lobes (GL) level at the three following distances: $r^F/2$, r^F and $2r^F$.

Depth		Dynamical	Spherical	Conical	Toroidal	Outer Rings
Axial Intensity (dB)		0	-3	-6	-7	-8.6
DF (mm)		-	30	80	100	38
r^F	BW-6dB (º)	3	3	4	5.5	2.3
	BW-20dB	6	6	14	18	15
	GL	-34.5	-34.5	-31	-30	-31.5
$r^F/2$	BW-6dB	3	12	18	17	2.5
	BW-20dB	6	26	38	38	28
	GL	-34.5	-25	-19	-18	-28
$2r^F$	BW-6dB	3	3.2	2.5	3	2.3
	BW-20dB	6	8.5	7	12	18
	GL	-34.5	-35.5	-33	-32	-31

TABLE 1

COSINE APODISATION

Apodisation is an amplitude modulating function used to reduce sidelobes, but at the expense of widening the upper part of the ultrasonic beam and, therefore, of decreasing the resolution. A great amount of apodization functions have been proposed in literature (Gaussian, cosine, cosine^2, Barlett, Hamming, Hanning, Blackman are only some examples). The comparison of these functions is out of this work, as they produce rather similar results. Our purpose is to show the effect of one of these functions (i.e.: cosine) over the main beam and grating lobes of SA arrays:

$$A(i) = \cos(\pi\sqrt{x_i^2 + y_i^2}/D) \qquad [3]$$

Figure 3-b shows the pressure axial profiles for the array configurations applying the cosine apodisation and steering the beam 30º in elevation. In Table II, the same parameters of Table I describing the beam quality are shown for the apodisation case. Figure 4 shows the B-class representation of the steered beams produced by the four array configurations.

Depth		Dynamical	Spherical	Conical	Toroidal
Axial Intensity(dB)		-7	-9	-10.6	-10.7
DF (mm)		-	35	75	90
rF	BW-6dB	4	4	4.5	4.6
	BW-20dB	7	7	10	10
	GL	-31	-31	-30	-29
$r^F/2$	BW-6dB	4	7.5	8.5	8
	BW-20dB	7	17	22	23
	GL	-31	-27	-25	-24.5
$2r^F$	BW-6dB	4	4.3	4	4
	BW-20dB	7	9	7	7.5
	GL	-31	-31	-31	-30

TABLE 2

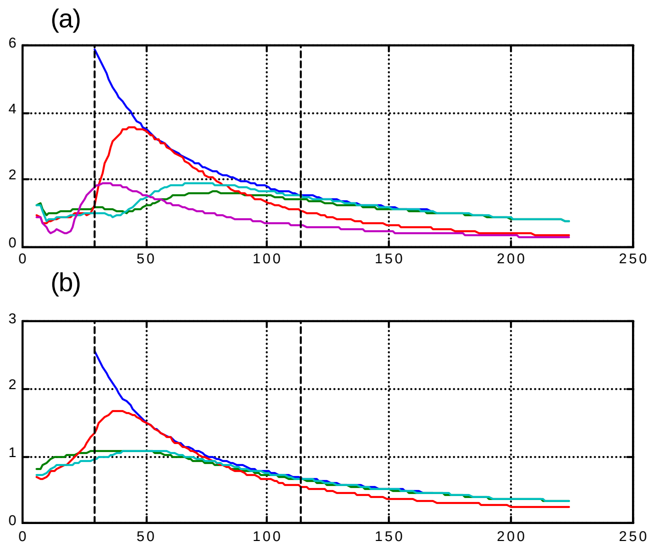

Figure 3. Axial field distribution of acoustic pressure. (a) Uniform apodisation (b) Cosine apodization. Profiles represented : Toroidal lens (Blue), Conical lens (Red), Spherical lens (Green) and Outer ring spherical focussed (Cyan).

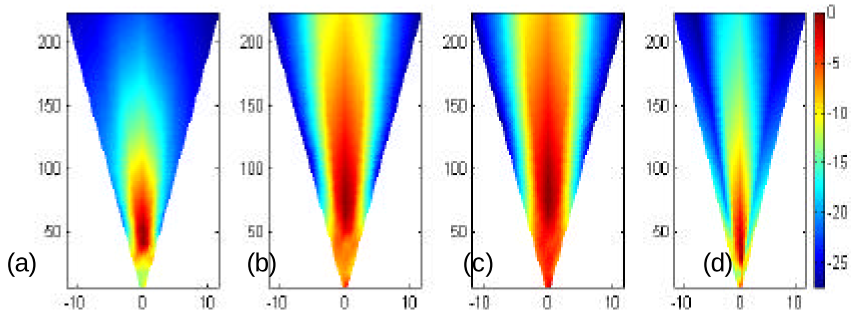

Figure 4. B-scan representation of the beam transmitted by the SA array with spherical focusing (a), conical (b), toroidal (c) and three outer rings (d) respectively. The axes are given in mm.

DISCUSSION AND CONCLUSSIONS

From figure 3-a the axial response of the different array configurations can be compared. An effect of steering over all configurations is a softening of their axial profiles with the corresponding reduction of their differences.

The spherically focused array produces a sharper beam in the axial direction, with a peak of amplitude almost doubling the one of the rest of lens profiles, but the depth of field (DF=30mm) is very short. The loose of axial intensity, measured as the integral of pressure amplitude between the depths $r^F/2$ and $2r^F$, with respect to dynamic focusing is -3dB. The angular beamwidth at the focal depth is 6º at -20dB, which is much better than the other configurations. For points in the pre-focal zone, the beam characteristics become worse, but they still are advantageous over the other array configurations. In the post-focal zone, the beam maintains good quality with respect to the beamwidth and GL relative level. The effect of apodisation over spherical focusing can be specially observed at the pre-focal zone, where the beam improves GL level and lateral resolution. In contrast, these parameters worsen slightly after the focus.

The conically focused array (axicon) produces a clear enlargement of the depth of focus (DF= 80mm). The axial intensity in the zone $r^F/2$ to $2r^F$ is -3dB with respect to the spherical lens, but the pressure amplitude at large distances become higher. The side lobes produced by this lens configuration cause that the lateral resolution at the lower beam levels is worse. Figure 4 shows how axicons produce beam have a constant wide (in mm) as they progress along the axis, in contrast with spherical focusing that produces beams of constant angular width. For this reason, axicons have low angular resolution in the pre-focal zone, but this clearly improves in the post-focal zone. Apodization does not enlarges the depth of focus of the conical lens, but it improves the beam quality of the pre-focal zone and, in general, the lower part of the main beam.

The toroidal lens produces the beam of largest depth of focus. However, it also presents poorer results for lateral resolution.

The outer rings of the array can be used for transmission because permit reducing the number of active elements. The beam has very good lateral resolution at all depths for the -6dB cutting level, however side lobes cause the beam widens in its lower part.

SA arrays have the property of producing a main lobe of good quality and, moreover, producing grating lobes (GL) of low amplitude. This property allows designing SA arrays with inter-element distances even larger than a wavelength, in contrast with 2D arrays of squared pattern. For instance, in tables 1 and 2, the GL level of the transmitted beam is below -30dB almost in all cases, which is enough for most ultrasonic imaging applications. The GL amplitude mainly depends on the steering angle θ, the inter-element spacing, the size of elements and the number of elements in the aperture. The influence of the lens profile and even of the apodisation function on the grating lobes amplitude is however limited to a few dB. Most of the variations (relative to the main lobe) appearing in tables 1 and 2 are due to deteriorations of the main lobe in the near field, instead an increase of the GL level.

From this analysis we can conclude that axicons can be used in transmission because they produce a beam of very large depth of focus and constant wide. Sidelobes from axicons are higher than in the case of spherical focusing specially in the pre-focal zone of the field. Moreover, grating lobes are little affected by the lens profile. Apodisation improves resolution at the lower levels of the main beam. In contrast, it worsens the beamwidth at high level of amplitude and grating lobes.

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