BEAMFORMING WITH ACOUSTO-OPTICAL COMPONENTS

DIRK RATHJEN

Fried. Krupp GmbH Krupp Atlas-Elektronik, Sonar Research Department
P. O. Box 44 85 45, D-2800 Bremen 44, West Germany

RESUME

A mesure que l'on approche les limites du traitement de signaux électroniques, les méthodes optiques deviennent de plus en plus séduisantes. Dans les cas d'antennes équipées de capteurs, la formation de faisceaux est un moyen couramment utilisé dans le traitement des données. Le présent article renferme une description relative à la réalisation d'un formeur optique de faisceaux pour antennes linéaires.

Le mode de fonctionnement de ce formeur de faisceau est similaire à la méthode de compensation de phase. Chaque capteur de l'antenne est représenté par une source lumineuse modulée en fonction du signal de capteur reçu. Les sources sont disposées selon un modèle identique à celui des capteurs, mais à une échelle beaucoup plus réduite. Le modèle des faisceaux de lumière émis est dans l'espace filtre par un modulateur acousto-optique à grande ouverture, le fonctionnement du filtre est un cosinus de propagation à fréquence variable. Après le filtrage, le signal d'antenne est obtenu en recueillant la lumière au moyen d'une lentille, en le mesurant à l'aide d'un détecteur de lumière et en effectuant un traitement électronique postérieur. Pour les signaux monochromatiques, la commande du modèle de faisceau de l'antenne est effectuée en variant la fréquence spatiale de la fonction cosinus progressant dans le filtre.

Le type de formeur de faisceau est disponible dans notre laboratoire en tant qu'ensemble expérimental. Les mesures sont effectuées au moyen de signaux a basse fréquence produites de façon synthétique. Cet article renferme le fond théoriques ainsi que les résultats expérimentaux.

SUMMARY

Approaching the capacity limitations of electronical signal processing optical methods become more and more attractive. Dealing with sensor arrays beamforming is a standard processing mode. In the present paper the realisaiton of an acousto-optical beamformer for linear antennas is described.

The mode of operation of this beamformer is similar to the method of phase compensation. Each sensor of the array is represented by a light source which is modulated due to the received sensor signal. The sources are arranged in a pattern identical to that of the sensors but in a substantially reduced scale. The pattern of the emitted light beams is spatially filtered by an acousto-optical modulator with large aperture. The filter function is a propagating cosine with variable frequency. After the filtering the antenna signal is obtained by collecting the light by a lens, measuring it by a photodetector, and executing an electrionic post-processing. For monochromatic signals the steering of the antenna beampattern is performed by varying the spatial frequency of the propagating cosine filter function.

That kind of beamformer exists as an experimental set-up in our laboratory. Measurements are accomplished with synthetically generated low-frequency signals. Theoretical background and experimental results are presented.

BEAMFORMING WITH ACOUSTO-OPTICAL COMPONENTS

DIRK RATHJEN

1. Introduction

On many fields of signal processing the demands on the processors grow more and more. Concerning antennas the number of sensors becomes still larger. This is directly connected with the increase of the number of signal channels which have to be processed. Thus it is tried to derive profit from the favourable qualities of optics, which has among others the advantage of the capability to process many channels parallel.

Inspired by a proposal of Hetland et al. [1] we built an acousto-optical beamformer for linear antennas working similar to the method of phase compensation. In the following the principle of operation is described illustrated by some theoretical relations. Furtheron the experimental set-up is explained and finally the results are presented.

The beamformer exists as a large and heavy laboratory set-up being not suited for operation in practice for many reasons. Nevertheless, transfered to other technologies this kind of beamformer hold out a prospect of small and light moduls for large antennas.

2. Description of the acousto-optical beamformer

Before explaining the method in the next chapter a phenomenistic description should be given with the aid of figure 1.

On the x-axis on the left side a linear sensor array with arbitrary pattern is sketched. In our set-up each sensor of the array is represented by a laser. Its light intensity is modulated due to the received sensor signal. The lasers are arranged on the ξ-axis in a pattern identical to that of the sensors but in a substantially reduced scale M ($\ll$1). The pattern of the emitted light beams is spatially filtered by an acousto-optical modulator (AOM) with large aperture. The filter function is a propagating cosine with variable frequency f_k. After the filtering the antenna signal is obtained by collecting the light by a lens (L), measuring it by a photodetector (PD), and executing an electronical post-processing (PP). For monochromatic signals steering of the antenna beampattern is performed by varying the spatial frequency of the propagating cosine filter function.
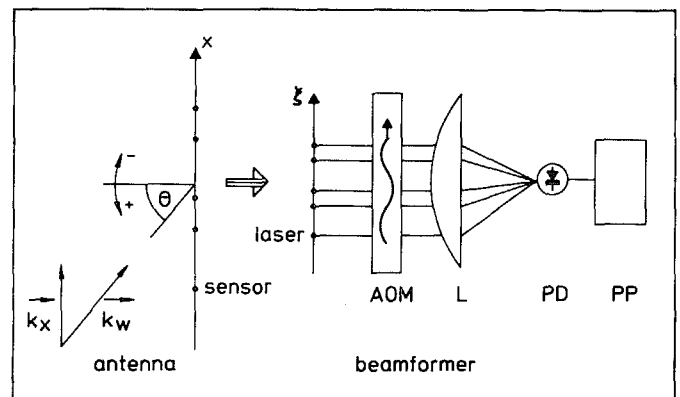

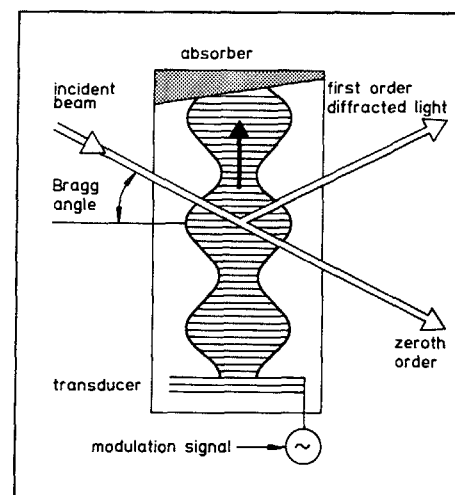Fig. 1. Principle of the acousto-optical beamformer.

Fig. 2. Acousto-optical modulator.

The acousto-optical modulator is the principal item of this beamformer. It consists of a block of a transparent material (e.g. glass) with a transducer for high frequency acoustic waves fixed at one side (see figure 2). These waves are continuously traversing the device and are absorbed on the opposite side to avoid reflections and the resulting standing waves. By the photoelastic effect the acoustic waves induce a modulation of the refraction index in the medium. If you use a monofrequent wave a sinusoidal phase grating is built up which diffracts an incident light beam.

Since the grating is extended in depth we have to concern Bragg diffraction, i. e. if it is irridiated by light under the Bragg angle there exist mainly the zeroth and first order of diffraction. The intensities of the orders are regulated by the amplitude of the acoustic wave. In figure 2 the signal to be impressed on the incident light is to

BEAMFORMING WITH ACOUSTO-OPTICAL COMPONENTS

DIRK RATHJEN

be seen as the envelope of the high frequency carrier. It marks the different modulation depths of the phase grating. This illustration makes evident that if you consider e. g. the first order such a Bragg cell is not only a time but also a space dependent attennuation device, i. e. a time variable spatial filter.

3. Theoretical background

The power beampattern $P(k_x)$ of an antenna is described by the spatial Fourier transformation (FT) of the antenna function $f(x)$

$$P(k_x) \sim \left| FT \left\{ f(x) \right\} \right|^2 . \tag{1}$$

k_x is the x-component of the wave vector $\vec{k_w}$ of a monochromatic sound wave incident at angle θ to the antenna normal (see figure 1)

$$k_x = k_w \cdot \sin\theta , \quad k_w = \frac{2\pi}{\lambda_w} = 2\pi \frac{f_w}{c_w} . \tag{2}$$

c_w is the sound velocity in the medium (e.g. water); λ_w and f_w are wavelength and frequency of the wave. The antenna function is the description of the geometrical configuration of the individual antenna sensors with their possible amplitude and phase weightings. An unweighted linear antenna receives maximum power from plane waves incident along the antenna normal ($\theta = 0°$, $k_x = 0$). For waves from other directions the received power decreases normally. k_x is nonzero, i. e. the waves have a momentum in x-direction. Beamforming in the direction θ' now means to compensate the corresponding momentum k_x' - in other words to shift the beampattern $P(k_x)$ by k_x'. This is done in the space domain by a multiplicative spatial filter which delivers the momentum $-k_x'$.

In the case of the well-known phase compensating beamformer this filter has a linear increasing phase and a constant amplitude. Its function is $\exp(ik_x' \cdot x)$. In our case it has the sinusoidal amplitude function $\cos(k_x' \cdot x)$. That is the real part of the complex filter function in the phase compensating case.

Translating these filters for demonstration in wave-optical components fixed in front of the antenna they are equivalent to a large "prism" and a large "diffraction grating", respectively. Both

components are dimensioned in "prism angle" and "grating constant" so that after refraction and diffraction, respectively, the incoming wave is normally incident on the antenna.

Now in our case by filtering there results the new antenna function $f(x) \cdot \cos(k_x' \cdot x)$ which with equation (1) leads to the beampattern

$$P_M(k_x) \sim P(k_x - k_x') + P(k_x + k_x') . \tag{3}$$

$P_M(k_x)$ is the sum of two original beampattern $P(k_x)$ which are shifted by $\pm k_x'$.

In contrast to the electronical verifications of the spatial filter in the phase compensating beamformer the filter in our beamformer exists in reality in form of the acousto-optical modulator - of course not on the large real antenna but on its substantially reduced image on the ξ-axis. With the frequency f_k above mentioned an amplitude grating $\cos(k_\xi \cdot \xi)$ is built up with

$$k_\xi = \frac{2\pi}{\lambda_k} = 2\pi \frac{f_k}{c_k} . \tag{4}$$

k_ξ is the propagation constant of the plane acoustic modulation wave in the modulator medium. λ_k is the wavelength and c_k the sound velocity. The axis transformation is described by the relation $\xi = M \cdot x$ and therefore it is

$$k_x' = M \cdot k_\xi . \tag{5}$$

In the general broad-band case each modulation frequency f_k causes a symmetrical shift of the beampattern of the above mentioned k_x' value. In the narrow-band case it means a symmetrical steering to an angle θ' from the antenna normal. The functional connection is

$$f_k = \frac{1}{M} \cdot \frac{c_k}{c_w} \cdot f_w \cdot \sin \theta' , \tag{6}$$

which results from (5). For originally symmetric beampattern $P(k_x)$ also $P_M(k_x)$ is symmetric and therefore ambiguous. Thus, by this means only the magnitude of k_x' can be detected. The sign is obtained by the following frequency consideration.

The spatial modulation wave is propagating in positive ξ-direction. Therefore incident waves with

BEAMFORMING WITH ACOUSTO-OPTICAL COMPONENTS

DIRK RATHJEN

positive k_x-components obtain a negative Doppler shift and vice versa. Both components can be separated by an appropriate filter electronic. Thus, scanning the k_x-spectrum is performed by varying k_ξ, i. e. by varying the modulation frequency f_k. Considering both frequency components in the narrow-band case the antenna is steered simultaneously to positive and negative angles θ'.

4. Experimental set-up

The concept dealt with above is realized in an experimental set-up in our laboratory. Figure 3 gives a detailled sketch of its geometrical and electronical configuration.

Four laser modulator systems (LM) on the left side represent four antenna sensors. They consist each of a 1 mW HeNe-Laser and a small acousto-optical modulator which modulates the laser light intensity according to the signal amplitude received by the corresponding sensor. This is managed by a control device (CD). The intensities can be adjusted by polarizers (P). To obtain the desired pattern of the laser beams alignment is done with four mirrors (M).

The beamforming spatial filter is built up in the acousto-optical modulator (AOM) which is controlled by a driver (D) and a sweep generator (SG). The momentary modulation frequency is f_k. A first lens (L1) accomplishes a Fourier transformation of the modulator output pattern. In its focal plane zeroth and first order of the diffracted light (see chapter 2) can be separated by a stationary spatial filter (SF). Finally a second lens (L2) forms an image of the filter aperture on a photodetector (PD).

Though using lasers our method works incoherently. The signal amplitudes of the electronical side correspond to light intensities. Therefore with the signal representation as well as with the filter function a bias has to be added. This produces falsifying terms in the photodetector signal which are partly eliminated in a compensator (C). Then its output is a signal with the three frequency components

$$f_k - f_w, \; f_k \; \text{and} \; f_k + f_w \; . \qquad (7)$$

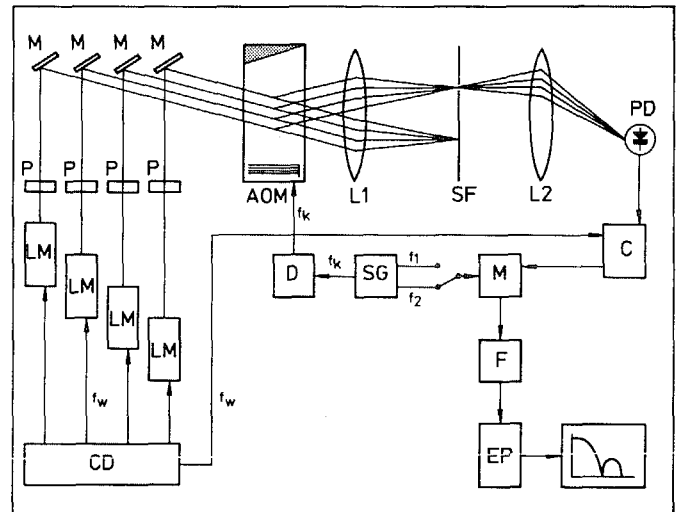These are separated in a filter (F) after being mixed down in M . The appropriate mixing frequen-

Fig. 3. Scheme of the experimental set-up.

cies f_1 and f_2 are produced by the sweep generator in parallel to the f_k-sweep. We use

$$f_1 = f_k - f_w/2 \;\; \text{and} \; f_2 = f_k + f_w/2 \qquad (8)$$

and obtain in both cases the desired signal component by band pass filtering with $3/2 \cdot f_w$ as center frequency. In this case mixing with f_1 means antenna steering to negative angles θ' mixing with f_2 to positive ones (see figure 1).

Finally an end processor (EP) forms the power mean of the filtered signal which then can be recorded versus the spatial filter frequency f_k.

5. Measurements

In this chapter we present two beampattern recorded by the acousto-optical beamformer. For this purpose we simulate a monochromatic signal incident from the antenna normal and variate the steering angle θ'. The antenna is assumed to consist of four sensors with equidistant spacing receiving identical signals. In this constellation the signal components with the three distinct frequencies of (7) give the same pattern. The mixer and filter for sign discrimination can be omitted. For the rest the arrangement is as sketched in figure 3.

The laser beams have a spacing of $d = 10$ mm and a diameter of about 1 mm at the AOM locus. Beampattern with three frequencies f_w = 0.1, 1 and 10 kHz are

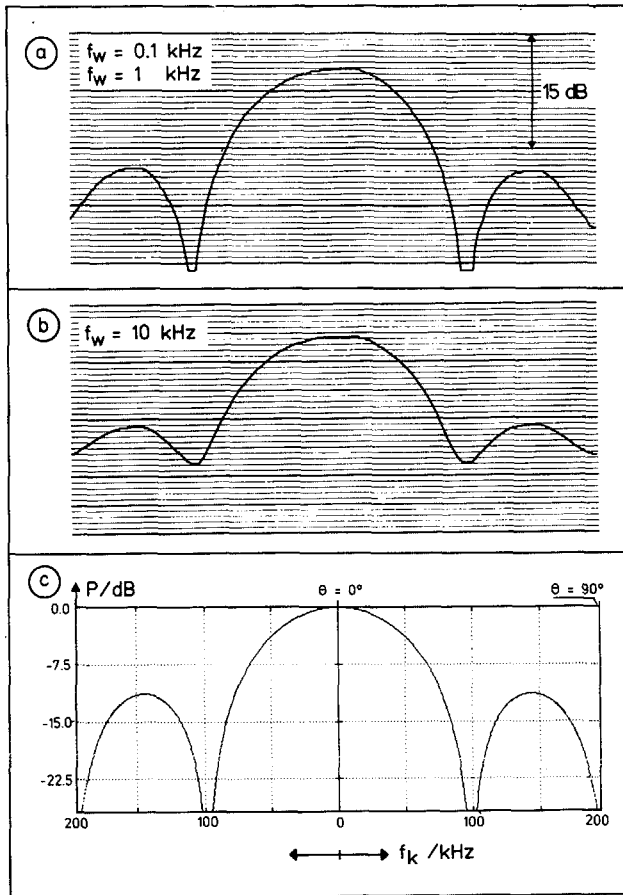# BEAMFORMING WITH ACOUSTO-OPTICAL COMPONENTS

Dirk Rathjen

Fig. 4. Beampattern for $D = \lambda_w/2$
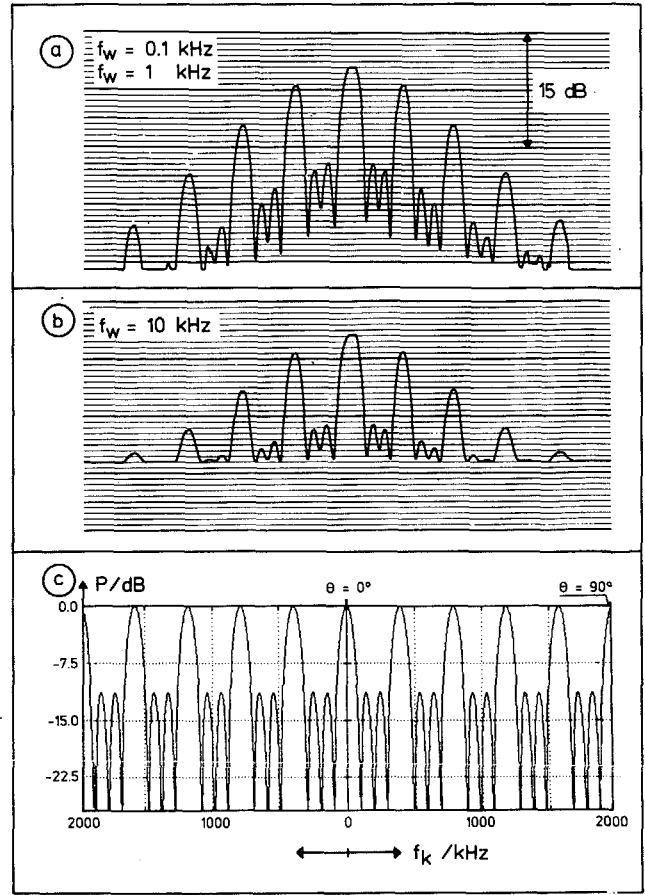a, b) measured and c) theoretical.

Fig. 5. Beampattern for $D = 5 \cdot \lambda_w$
a, b) measured and c) theoretical.

recorded. A sweep of 2 - 200 kHz as well as one of 2 - 2000 kHz is applied as filter frequency f_k.

In figures 4 and 5 the results of the measurements are reproduced. The sections a) show original records with $f_w = 0.1$ and 1 kHz which cannot be distinguished from each other. Sections b) give the curves for 10 kHz. At the bottom (c) the theoretical functions are displayed. In all diagrams the power P is plotted versus filter frequency f_k for a downsweep followed by an upsweep. The symmetry of the curves gives information about reproductivity of the measurements.

The relation between filter frequency f_k and angle θ' is given by equation (6). Assuming a sensor spacing of $D = \lambda_w/2$

$$M = \frac{d}{D} = 2\frac{d}{\lambda_w} = 2\, d\frac{f_w}{\cdot c_w} \qquad (9)$$

is valid. Herewith equation (6) becomes

$$\sin \theta' = 2\, d\frac{f_k}{c_k} \quad . \qquad (10)$$

With the given value of d and c_k = 3932 m/s (AOM,SF8 glass) the angle θ' = 90° corresponds to f_k = 196.6 kHz. Therewith figure 4 shows the angle range of 0° - 90° twice. The same range is displayed in the beampattern from figure 5 but for an antenna with a ten-times larger sensor spacing ($D = 5 \cdot \lambda_w$). Since this antenna is not occupied closely enough this spatial subsampling leads to numerous ambiguities (grating lobes) which are reproduced well by the optical beamformer. The power decrease to high frequencies has mainly three reasons.

1. The finite laser beam diameter has the consequence of a nonomnidirectional beampattern of its own (the "laser sensor beampattern") which is a multiplicative term in the antenna beampattern.

2. The alignment of the laser beams concerning the equidistant spacing is more sensitive with high filter frequencies.

3. The measuring electronic cannot cover the full frequency range in our momentary experimental equipment.

BEAMFORMING WITH ACOUSTO-OPTICAL COMPONENTS

DIRK RATHJEN

A detailed quantitative interpretation is not yet done. The same is true for the bias in the $f_w = 10$ kHz measurements.

6. Conclusions

In the present paper theory and experimental set-up of an acousto-optical beamformer are described. In function and result it is almost equivalent to a phase compensating beamformer. Its complex spatial filter function is here reduced to a real one. This causes an ambiguity in the sign of the antenna steering angle. Still, the sign discrimination can be done by a frequency consideration.

Such a beamformer is built up in our laboratory. Two recorded beampattern of linear four sensor antennas, each with different equidistant spacing, are presented. Both correspond well to the theoretical predictions.

Our work should be seen as a step in the direction of the future conception of an extensive optical signal processing including integrated optics with all its very promising qualities.

Reference

[1] G. Hetland, C. M. Davis and R. E. Einzig "Optical Sonar System Concepts", EASCON 79, IEEE Electronics and Aerospace Systems Conference, Part III., 1979, p. 602 - 609.