TRANSMISSION PATTERN OPTIMIZATION FOR BROADBAND ACTIVE SONAR ANTENNAS

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Abstract: *To achieve a desired steering direction or beamwidths transmit antennas in sonar applications usually apply an optimized amplitude and time-delay or phase shading to the individual transducers. Modern active sonar Systems usually operate at larger bandwidths using frequency modulated signals and subsequent matched filtering to maximize the signal to noise ratio. Nevertheless the shading parameters are usually estimated based on monochromatic evaluations e.g. for center- and edge frequencies due to computational reasons. Hence to ensure the performance including the undistortedness of the signal a broadband optimization criterion should be applied.*
In this paper the shading parameters for a sonar transducer array are optimized to achieve a desired transmission pattern at the matched filter output of the consecutive processing chain. Each transceiver of the antenna is modelled by a single source with an inherent characteristic to calculate the superposition of the delayed signals at a given range or in the far field. The shading parameters are obtained by exploiting numerical optimization techniques. Finally, the transmit characteristics obtained by the broadband and the narrowband optimization are compared by their angular dependent matched filter response.

Keywords: *Beamforming, Numerical Optimization, Numerical Acoustics*

1. INTRODUCTION

For sonar transmitters it is often desirable to provide a constant source level over a wide angular width while transmitting no power elsewhere [1]. The realization is only possible approximately due to limited antenna lengths and a limited amount of transmitters. Similar to electronic filters this results in degradations like passband ripples, a transition band with limited steepness and a stopband with finite attenuation.

To achieve a desired steering direction or beam widths optimized amplitude and time-delay or phase shading are applied to the individual transducers [2] which are mostly calculated by numerical optimization methods.

In the conventional beampattern calculation monochromatic waves are assumed to determine the resulting superposition in a distinct point or in the far field. This simplification allows a fast computation of the beampattern and therefore a faster optimization which is one reason for its common use. However, most acoustical active antennas apply frequency modulated (FM) pulses with broader bandwidths. In order to determine the beampattern for those pulses a time-signal-based beampattern calculation based on the matched filter output is introduced.

In this paper the conventional beampattern calculation – based on an infinite continuous wave – and the introduced matched filter beamforming – based on pulses of finite duration– are investigated and the results are compared. Finally these are used to optimize the shading coefficients of a linear transmit antenna and the effect of different signal types and pulse lengths are displayed.

2. CONVENTIONAL BEAMPATTERN CALCULATION

In the conventional beampattern calculation each transducer is modelled as a single sound source. The superposition of the monochromatic signals emitted by N transducer elements and observed in point $\boldsymbol{P}(\varphi, \theta, R)$ can be represented by the complex beampatter

$$bp(\boldsymbol{P}, f) = \frac{1}{\hat{Q}} \sum_{n=1}^{N} Q_n(\boldsymbol{P}, f) c_n(\boldsymbol{P}, f) e^{jkr_n(\boldsymbol{P})} \tag{1}$$

with the normalization constant $\hat{Q}$, the complex shading parameters

$$Q_n(\boldsymbol{P}, f) = a_n e^{j2\pi\hat{\tau}_n f}, \tag{2}$$

depending on the amplitude and time-delay parameters a_n and $\hat{\tau}_n$, the inherent n-th element characteristic $c_n(\boldsymbol{P}, f)$, the wave number $k = 2\pi f/c$ and the distance to the observation point $\boldsymbol{P}$

$$r_n(\boldsymbol{P}) = \left| \boldsymbol{P} - \begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix} \right|. \tag{3}$$

The logarithm of the squared magnitude of the narrowband complex beampattern given by

$$BP_N(\boldsymbol{P}, f) = 20\,\lg(|bp(\boldsymbol{P}, f)|) \tag{4a}$$

is denoted as beampattern. For broadband signals the beampattern is integrated over the bandwidth B, which can be approximated by the Riemann sum

$$BP_B(\boldsymbol{P}, f) = 20\,\lg\left(\frac{1}{B}\left|\int_B bp(\boldsymbol{P}, f)df\right|\right) \approx 20\,\lg\left(\frac{1}{I}\left|\sum_{i=1}^{I} bp(\boldsymbol{P}, f_i)\right|\right). \tag{4b}$$

3. BEAMPATTERN CALCULATION IN THE TIME DOMAIN

In contrast to the conventional beampattern determination a beampattern calculation based on the matched filter correlation between the transmitted signal $s_{Tx}(t)$ and the received signal $s_{Rx}(t)$ on an observation point $\boldsymbol{P}$ is developed, which is the superposition of N signals shifted by the delay $\tau_n(\boldsymbol{P})$ in the time domain. This allows the use of finite pulse lengths and different signal types like frequency modulated (FM) signals with arbitrary bandwidths. The delay $\tau_n(\boldsymbol{P})$ is defined by

$$\tau_n(\boldsymbol{P}) = \hat{\tau}_n + \hat{\tau}_{P,n}(\boldsymbol{P}) - \tau_0 = r_n(\boldsymbol{P})/c + \hat{\tau}_n - \tau_0 \tag{5}$$

where $\hat{\tau}_{P,n}(\boldsymbol{P})$ is the travel time from the n-th transmitter to the observation point $\boldsymbol{P}$ and τ_0 the minimum mutual time delay which is subtracted to minimize the computational effort. The n-th delayed transmitted discrete signal with the length of M is given by

$$s_n(m, \boldsymbol{P}) = 1_{[0,T]}\big(mT_s - \tau_n(\boldsymbol{P})\big)\frac{a_n c_n(\boldsymbol{P})}{r_n(\boldsymbol{P})} e^{j\psi(mT_s - \tau_n(\boldsymbol{P}))}, \tag{6}$$

where T is the pulse length,

$$1_{[0,T]}(t) = \begin{cases} 1 & t \in [0, T] \\ 0 & elsewhere \end{cases}$$

denotes the rectangular function of duration T and $\psi(t)$ is the phase argument defined by the chosen signal type. The received signal at $\boldsymbol{P}$ is now given by the superposition

$$s_{Rx}(m, \boldsymbol{P}) = \sum_{n=1}^{N} s_n(m, \boldsymbol{P}). \tag{7}$$

The beampattern is then given by the maximum of the cross correlation between the received signal $s_{Rx}(m_1 T_s, \boldsymbol{P})$ and the transmitted signal $s_{Tx}(m_2 T_s)$

$$BP_{MF}(\boldsymbol{P}) = 20 \cdot \lg\left(\max_m \left|r_{s_{Tx}s_{Rx}}(m \mid \boldsymbol{P})\right|\right). \tag{8}$$

4. EXEMPLARY INVESTIGATIONS

In the following section the introduced matched filter based beampattern calculation BP_{MF} and the conventional beampattern calculation BP_N or BP_B with four different pulse types – CW (continuous waveform), LFM (linear frequency modulated pulse), HFM (hyperbolic frequency modulated pulse), and DFM (Doppler sensitive frequency modulated pulse) [3] are compared. All calculations are based on a linear transmit antenna with $N = 36$ equispaced elements inherent stave characteristic at pitch of 0.4λ.

Figure 1 shows the beampattern BP_N and BP_{MF} for the aforementioned antenna without amplitude and phase shading applied for different pulse lengths.

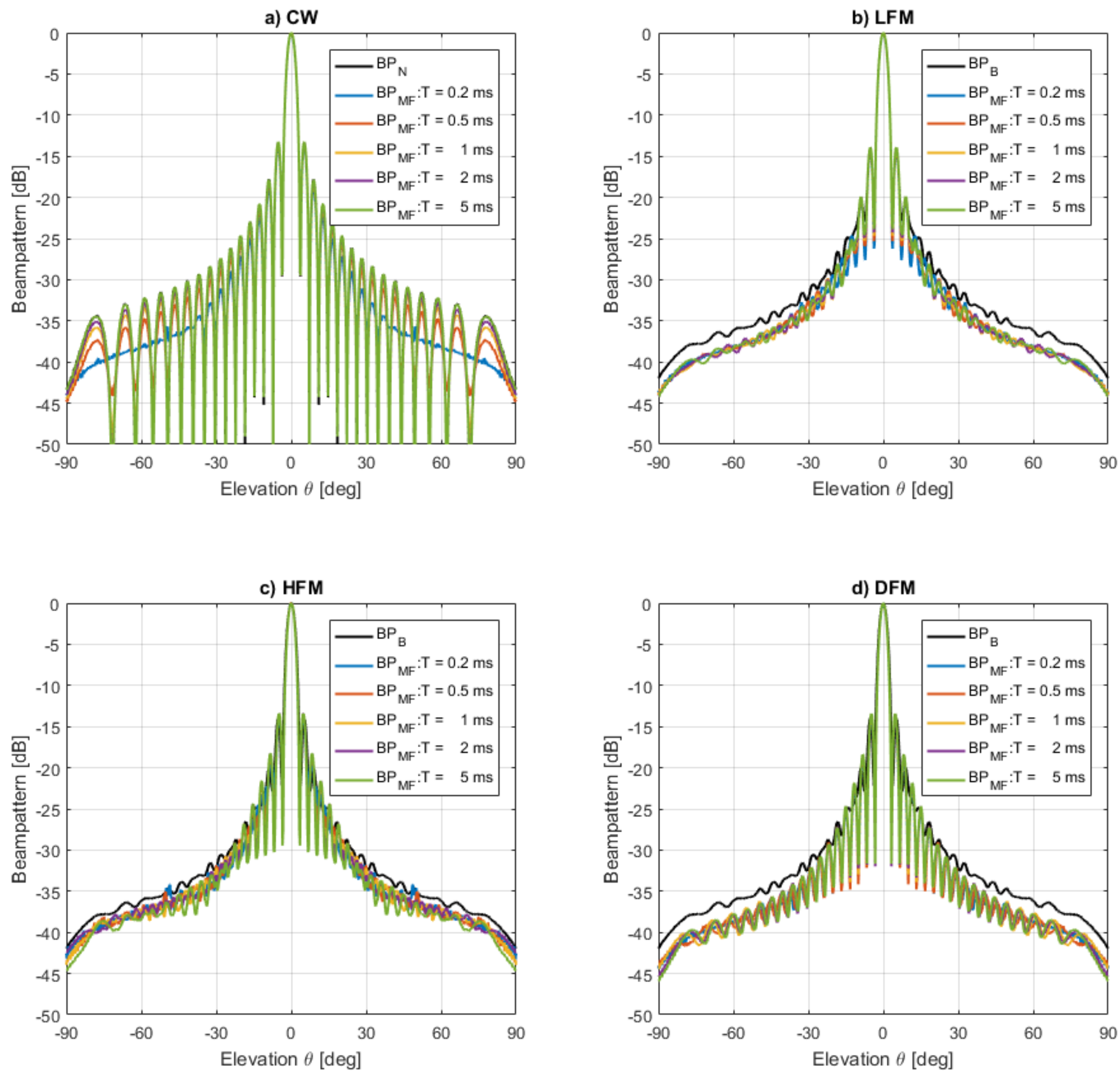

Figure 1: Comparison between the conventional beampattern calculation BP_N or BP_B and the matched filter base beampattern calculation BP_{MF} for different pulse types and durations T. The bandwidth for the FM pulses is set to B = $0.3f_c$. The black BP_N graph is masked by the light green BP_{MF} 5 ms graph.

In Figure 1a) for a pulse length of $T = 5$ ms the BP_{MF} matches almost perfectly with the BP_N. For lower pulse durations the notches are less distinct and the sidelobe level is decreasing. At the lowest investigated pulse length the BP_{MF} matches the shape of the broadband signals displayed in Figure 1b), c) and d) which results from the signal length induces bandwidth. The BP_{MF} for FM signals is significantly smoothed and also shows reduced ripples for decreasing pulse lengths. Here the BP_B has an equivalent shape but overestimates the sensitivity for higher incidence angles up to 3 dB for $\theta = 90°$.

In Figure 2 the degradations due to pulse length or type mismatch are investigated. The shading parameters a_n and $\hat{\tau}_n$ are optimized by numerical nonlinear optimization techniques [4] using a 5 ms LFM signal to provide a $60°$ beamwitdh with minimum ripple and a sidelobe suppression of 20 dB after a transition region of $10°$.

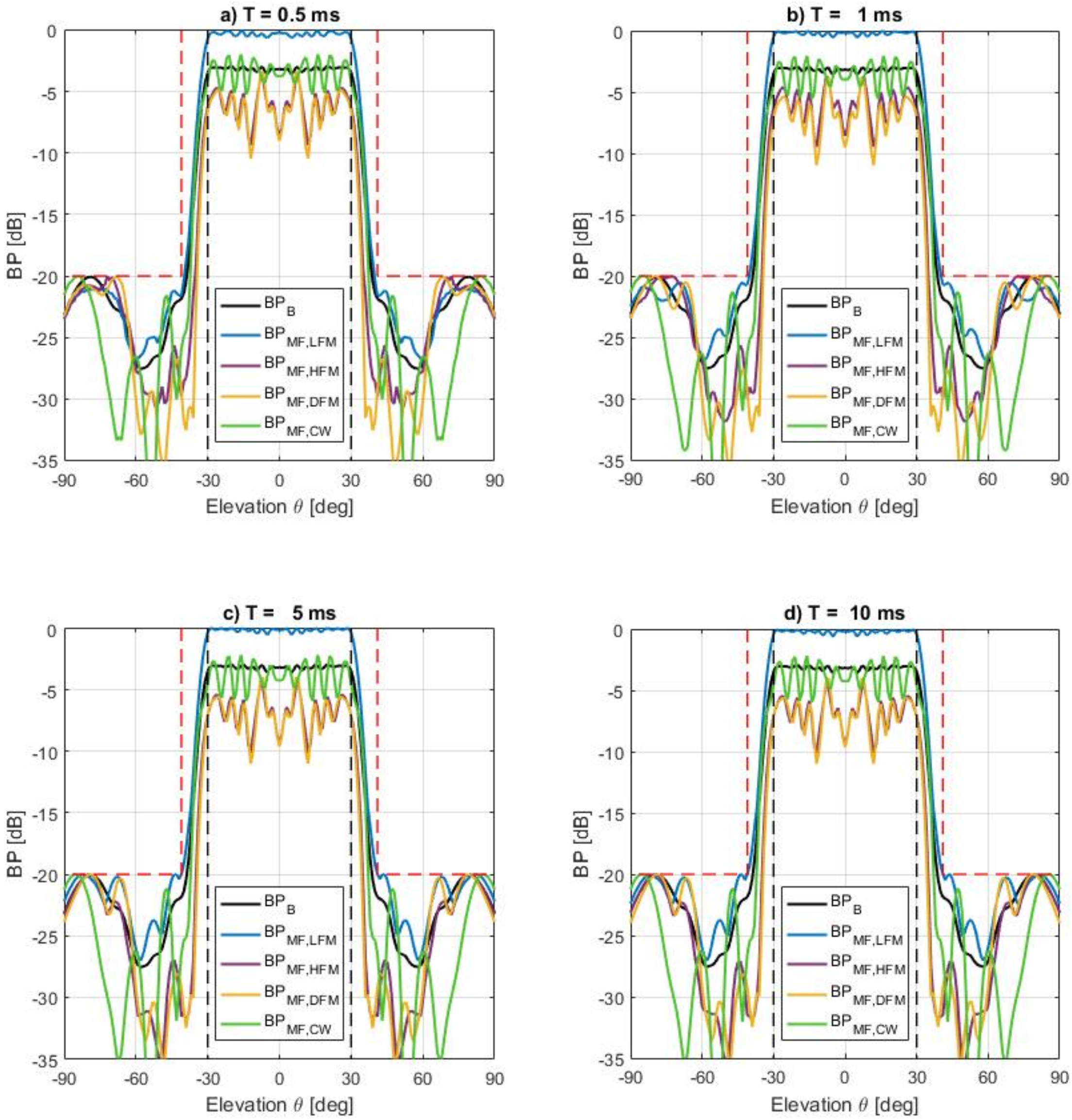

Figure 2: Beampattern obtained by one set of shading parameters for different calculation methods, signal types and pulse durations. The parameters result from an optimization with a 5 ms LFM signal. The graphs are normalized to satisfy the stopband restrictions.

For all pulse durations considered the BP_{MF} calculated with an LFM signal provides the desired characteristic with a slightly increased passband ripple as indicated in Figure 2a). The BP_B also provides a result with low ripple but with 3 dB less sidelobe suppression for large incidence angles. In addition to an increased ripple of 3 dB in the passband, the BP_{MF} calculated with a CW provides similarly reduced sidelobe suppression as the BP_B. The BP_{MF} calculated with an HFM and the DFM are comparable and provide the largest ripple and the lowest sidelobe suppression. Overall the investigated pulse lengths have minor influence on the calculated beampattern. Hence optimizing the beampattern requires separate shading parameter sets for all system pulse types but not necessarily for different pulse lengths.

5. CONCLUSION

In this paper we introduced a beampattern calculation technique based on the output of the matched filter of the consecutive signal processing chain and compared this to the conventional beampattern calculation for narrow and broad band signals. The introduced technique calculates the response of the antenna for a signal transmitted towards an arbitrary point. Nevertheless the computational effort is proportional to the pulse length of the applied signal being disadvantageous for numerical optimization methods.

The shading parameter optimization of an exemplary antenna using the matched filter based beampattern calculation technique provided the desired behaviour almost independent from the signal length. Nevertheless the same set of parameters proved to be unsatisfactory with other pulse types applied resulting in increased ripples and significantly lower sidelobe suppression. The conventional beampattern calculation provided a comparable result only degraded by the overestimated sensitivity at high incidence angles.

Future research should focus on a further adaption of the conventional beampattern calculation to better match with beampattern obtained by the matched filter based calculation for broadband application to combine processing speed and a better performance estimation.

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