Overview of Acoustic Holography and Beamforming techniques for Noise Sources recognition in open/closed environments: choosing the correct theory to apply for sound field reconstruction

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ABSTRACT

It is presented an Overview of existing Sound Images techniques like Acoustic- Holography or Beamforming and associated calculation methods like Music, Damas, Capon, orthogonal Beamforming, Sonah, with additional user defined alghoritms, in association with the use of 2 types of transducers: microphones (P) or Intensity probe (P-P or P-U). Full-digital front-end I2S, MEMS transducers and Open software architecture are also explained to allows most precise analysis of each of the different sound situation which requires full flexibility to perform right choices and improve results both in Near-field and Far-field Acoustic Imaging. Applications examples include indoor sound images inside vehicles and leaving spaces as well as noise sources identification on heavy machines and distant sources recognition in outdoor environments.

INTRODUCTION

Near-field Acoustical Holography (NAH) can perform source location with high spatial resolution even at low frequencies by measuring very close to the sound source and by reconstructing part of the evanescent near-field. Microphones distance (grid) with less than ½ wavelength is required, while the measurement area should cover in full radiating regions to avoid windowing effects.
These problems limit NAH method to 3-5 kHz depending on the number of the microphones and the overall diameter of the array.
Beamforming "BF" can provide good resolution at high frequencies with typically 40-90 measurement points, because it is possible to use irregular arrays at intermediate measurement distances. The spatial resolution at Low Frequency is lower than NAH as it depends from λ.
In practice, defining L as the distance source-array and D the array diameter:

- NAH offer a spatial resolution proportional to ½ λ in HF range
- NAH spatial resolution is proportional to array diameter D in the LF range
- BF spatial resolution is always proportional to L λ/D

Very generally speaking:
- NAH is preferable for low frequencies and small source-array distance
- BF is preferable for long source-array distance even if specific methods (Capon, Music) improve the Low Frequency resolution.

It may be concluded that both methods (NAH –BF) are surely need and the choice is to achieve 2 independent systems or "just one" implementing both at the same time on the specific array.

Arrays design

Various array designs exist that can provide good suppression of ghost images up to high frequencies, where the average element spacing is much larger than half a wavelength.
The use of two different arrays to perform the two types of measurement can be avoided considering to apply NAH at a short measurement distance and Beamforming at longer distance.
The possible array to match NAH and BF in a single array, should have irregular microphones distribution, and design today available are so called pseudo-random microphone distribution, with a number of microphones ranging from 40 to 60-80-100.
The Noise Inspector from CAE-Systems, implementing I2S Front-end, offer the choice of working as BF beamforming (delay and sum) or NAH nearfield acoustic holography (SONAH) with the same hardware.
In case of BF analysis there are also some options to improve Low frequencies resolution by using Capon method or MUSIC algorithm.
Moreover, custom algorithms can be easily implemented thanks to the open program architecture of the software.

Data Acquisition using I2S System

The First Frontend that supports new generation of sensors (MEMS with !²S), to allows many channels with minimum power consumption and low cost.
Sensors featuring: Interface I²S, High SNR 61 dBA, High Sensitivity-26 dBFS, Flat Frequency Response from 60 Hz to 15 kHz, Housing1/2'' standard.
The basic system I2S 40 channels can be configures as BF and/or NAH at your choice; the other methods and options can be implemented at any time.
The system main features includes: 40/64 channels,
- Sample Rate 48 kHz / 25 kHz
- Resolution 24 bits, Simultaneous Sampling
- Ethernet LAN

Configuration Examples:
Starting with I2S 40 channels – BF – wit the following options: Sonah (NAH), Music, Capon, Rotating BF
Alternative start with I2S 40 channels – NAH (Sonah)
With options as: "BF" + Music, Capon, Rotating BF.
All of the above methods-algorithms are public and are the same used by companies like BK, LMS, etc., the originality in I2S is the hardware efficiency and Low-price MEMS transducers, still with superior quality and Full-digital solution.

SONAH METHOD AND LASER VIBROMETER

There are several methods to use the microphone array signals which are based on standard Beamforming (BF), typically dedicated to measurements in the far field, and acoustic Nearfield Holography (NAH), a powerful way that - as the name already suggests – to investigate .
An important Criterion which distinguish the different methods from each other, is the capability on how sound sources should be separately (Resolution). The resolution is usually frequency dependent.

The NAH method provides not only information about theSound pressure information via the associated Variables such as sound velocity and sound intensity in the vicinity the sound radiating surface.
Compared with the Standard beamforming is especially the much better Resolution at low frequencies, a significant advantage
the method. The version used here (Statistically Optimised near field acoustic holography = SONAH) works both arrayed microphones, as well as with irregular arrangements. When Programming emphasis was on short computation times defined.

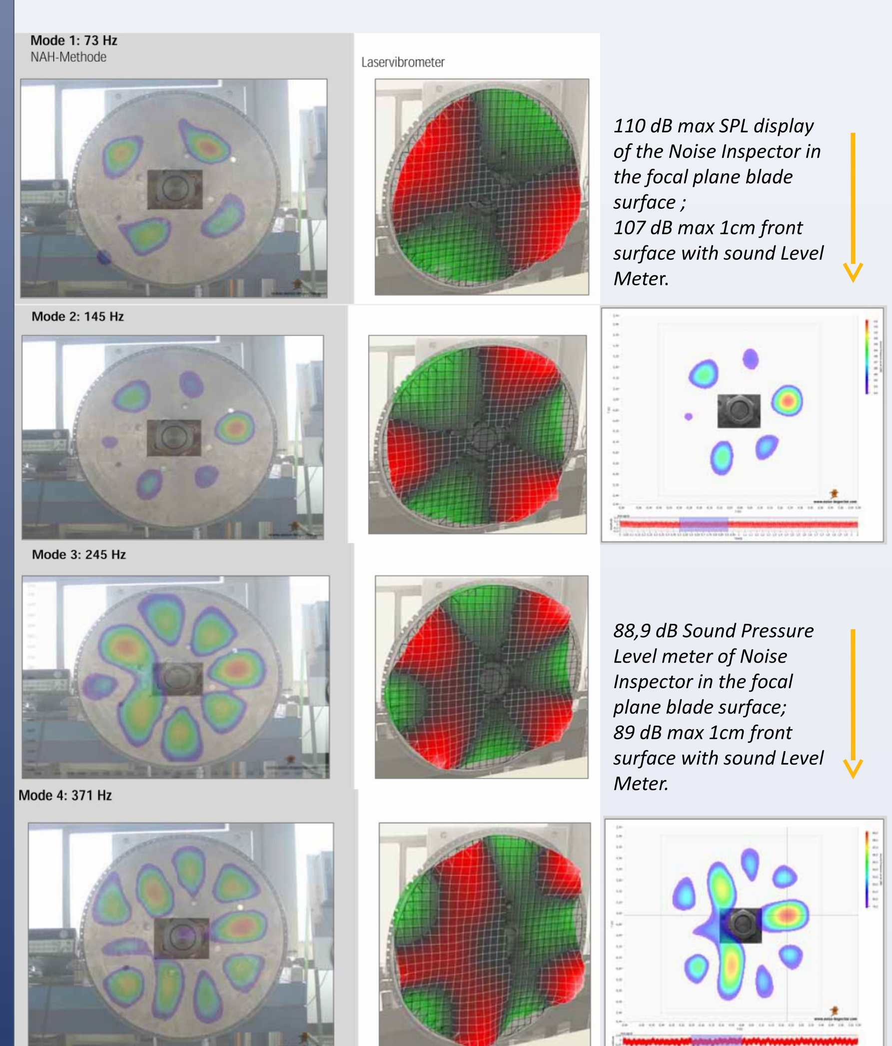
The SONAH algorithm implemented in the Noise Inspector has been used as an example of the application of the measurements of eigenmodes of a saw blade. The saw blade was stimulated at the left margin with a shaker. The Microphone array was used for the measurements at a distance positioned 15 cm in front of the saw blade.

The Experimental setup is shown in Figure at side.

Following pictures shows SONAH Results of the measurements, compared to similar investigations performed using a laser vibrometer .
Sonah-colored encodes the sound pressure level at the real surface of the vibrating structure.

In some measurements, the values of sound pressure level directly radiated by the radiating Surface were inspected with a sound level meter in parallel with the data provided by the laser vibrometer, giving velocity perpendicular to the surface of investigated structure.

The images shows results of the NAH method on the left side and color-coded results from Laser vibrometer on the rigth side.
Laser color coded being: Red = positive velocity, green = negative



110 dB max SPL display of the Noise Inspector in the focal plane blade surface ;
107 dB max 1cm front surface with sound Level Meter.

88,9 dB Sound Pressure Level meter of Noise Inspector in the focal plane blade surface;
89 dB max 1cm front surface with sound Level Meter.

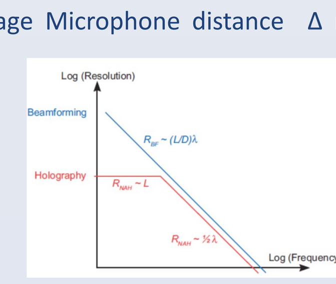
Number and location of sound sources match the locations at which the vibration velocity-speed of the blade surface has its maxima. For Mode 2 and Mode 4, it also reported the map of sound pressure level measured with a sound level meter, which can be compared with noise level map obbtained with the NAH Noise inspector. The NAH process works here up to frequencies of 73 Hz The use of beam forming method is usually demonstrating this - limited to frequencies above 800Hz
The great advantage of the NAH method in the low frequency Range.

THEORETICAL BASE

For both methods we consider frequency used *f* or the wavelength *λ*.
The relation is *λ = c * f*, where c = 340 m / s is the speed of sound.
In both methods R is the source-array distance (Measurement distance).

Beamforming

The geometric resolution Δ x for two adjacent sources is given by
Δx=(λ/D) R (1) , D is the diameter of the Microphone arrays.
In conventional applications and typical Distances of R = 1m is in the usable frequency range of 800 Hz to 12 kHz.
The upper limit is determined by the average Microphone distance Δ r limited to the array.
Example:
R = 1 m, D = 0.8 m, f = 800 Hz
With formula (1) results are:
Dx=(0.42/0.8) 1 = 0.5m
R = 1 m, D = 0.8 m, f = 2500 Hz
With formula (1) results are:
Dx=(0.13/0.8) 1 = 0.17m
It can therefore spatially resolve two separate sources which are not closer than 0.5 m and 0.17 m respectively, in the 2 frequency values.



Comparison - the quality of seperating sources betweenHolography and standard-beamforming.
L=Distance SourceArray,
D = Arraydiameter

Frequency Range:
fmin - fmax: 1000 Hz - 12 kHz
Spatial resolution of 1 m
Measuring distance: Δ x = 0.034 m - 0.4 m

Holography

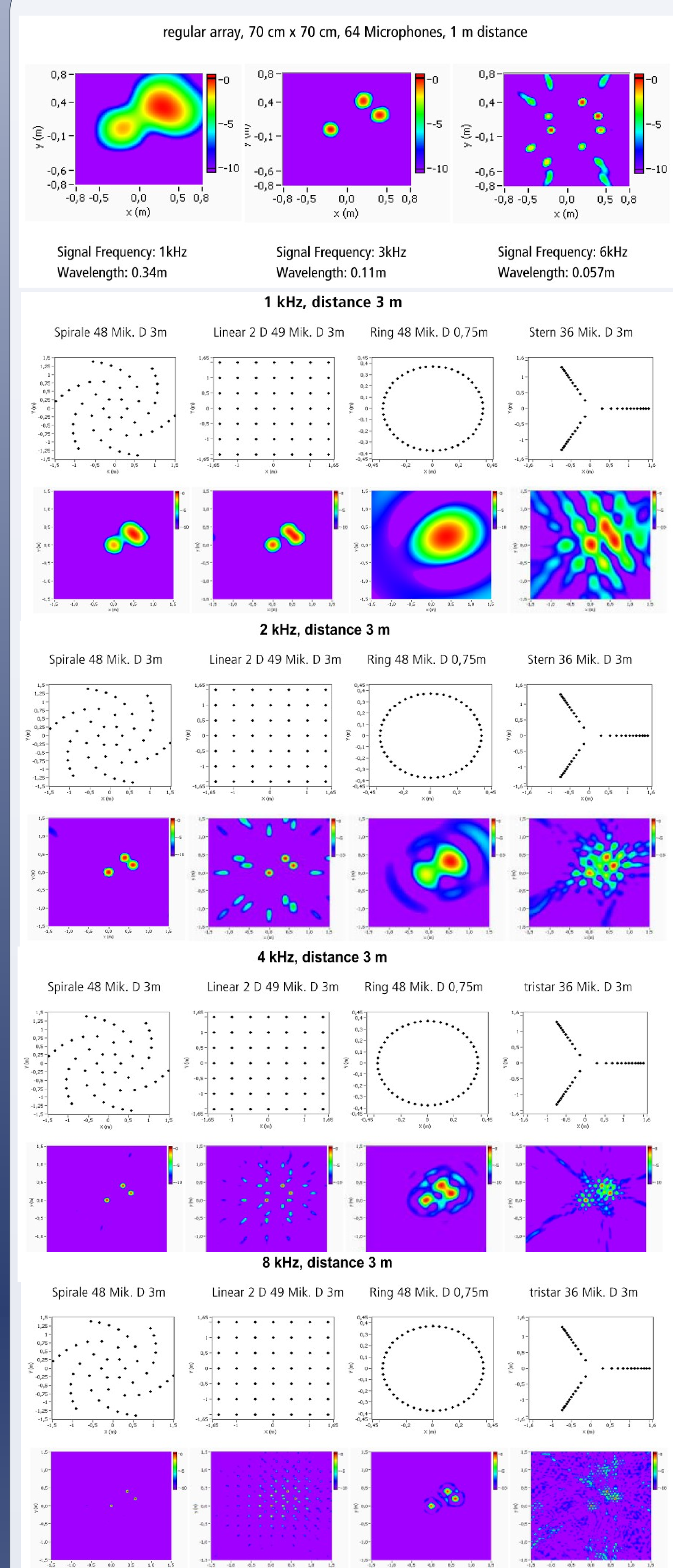
In the acoustic NAH near field holography, the geometric resolution Δ x is given by the measurement distance R, which is typically in the range of R = 5 cm - 10cm. Δx = R
The measuring distance, following the theory, shall be not smaller than the average distance of the microphone Δ r. This average distance is used also when microphones distance in the array is about Δ r = 10 cm.
There is no a real lower limit for Low Frequency (theoretically) and it is possible, in practical applications, to obtain reasonable results even at 100 Hz.
The upper limit for High frequencies fmax it is again the average microphones distance but, since the array has an irregular distribution, the limit is not sharp but fluid.
Fmax = c/2Δr = 1700Hz

Frequency Range
fmin - fmax: 100 Hz - 1700 Hz
Spatial resolution is 0.1 m
Measuring distance: Δ x = 0.1 m

At low frequencies and at around 1m distance from the source, Holography is a better choice in terms of resolution compare to Beamforming.

Arrays geometry

The following pictures shows the effect on spatial distribution of microphones in the different arrays, by reference to a standard linear array and as a function of frequency.



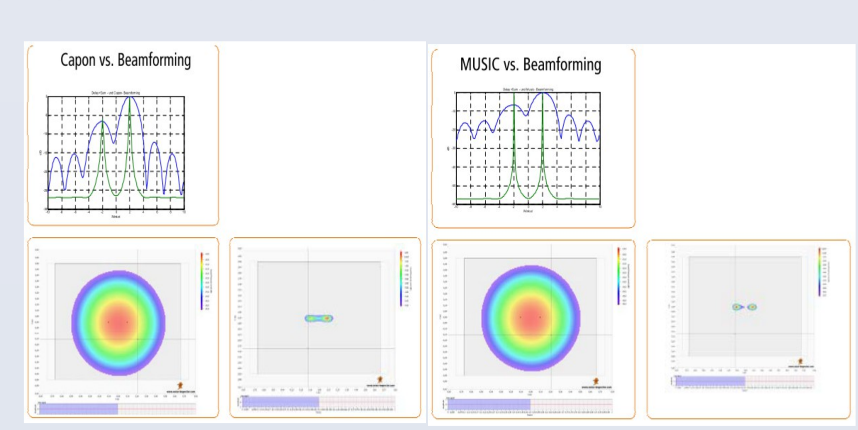
ALGORITHMS INTRODUCTION

The available algorithms list includes: Orthogonales Beamforming, MUSIC (Multiple Signal Classification), Capon, DAMAS, Rotating Beamforming, Holography (SONAH), user defined.

The choice among them is determined by distance from sources and spatial resolution vs. frequency range.

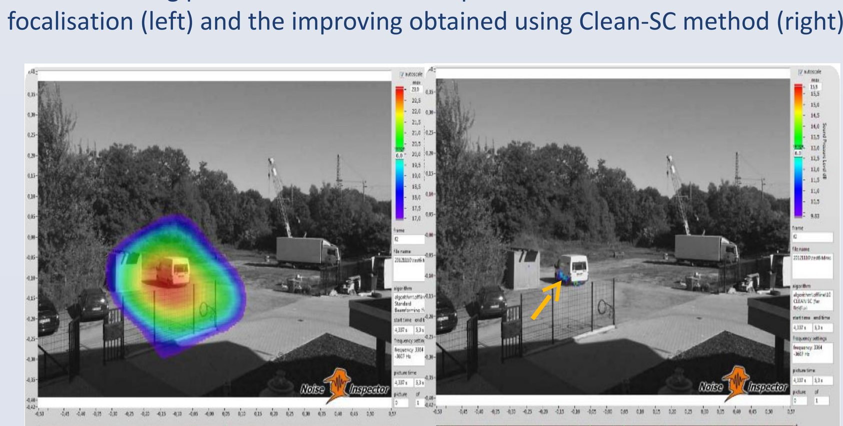
Capon and Music "vs." Beamforming ➔ *Near field*

Here in the following some comparative examples for a simulation of 2 ideal uncorrelated sources in 20 cm distance and Standard Array in 1 m, at the frequency of 500 Hz (1/3 octave).



Clean-SC "vs." Beamforming ➔ *Far field*

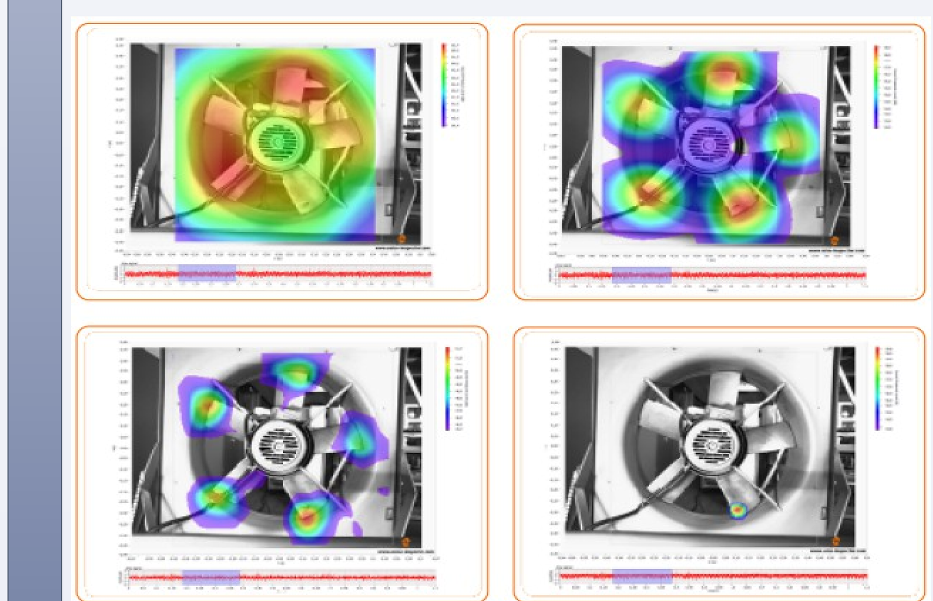
In the following pictures there is the comparison between standard BF focalisation (left) and the improving obtained using Clean-SC method (right).



The large and approximated source location on the left is obtained with standard beamforming, while on the rigth is can be seen the powerfull performance of the Clean-SC to perfectly localize the source (arrow indication).

Special *Rotating BF* application

An additional feature thanks to the high level of customizations and calculation power of this kind of system , allows to perform measurements of rotating machineries as a function of angle position. Here is an example for fan rotating at N=951 U/min, at the distance d= 60cm. Pictures refer to frequencies of 1000 Hz and 4000 Hz (top and left-right respectively), and frequencies of 2000Hz and 8000 Hz (bpottom left-right respectively).



Music algorithm

The Music (Multiple Signal Classification) algorithm, belongs to the class of "Subspace algorithms". The term refers to the subspace of the space Eigenvectors of the spectral matrix C of the MxM Microphone signals.
It can be shown that the matrix C in the presence of P sources, P large eigenvalues, and M-P small eigenvalues, has, corresponding to the noise in the system. (P = <M).
Each corresponding eigenvectors form the signal subspace and the noise subspace. The Eigenvectors are respectively orthogonal.
The separation of the eigenvalues is done by thresholding with an empirically determined threshold.
Furthermore, one can show that the steering vectors $\vec{S}(\theta_i)$ showing the P sources, i = 1 ... P orthogonal to the noise eigenvectors, where

$\vec{U}_k^N$ k = P +1 .... M.

$$\vec{S}^H(\theta_i) \bullet \vec{U}_k^N = 0$$

for i = 1 ... P and k = P +1 ..... M.

This property allows a pseudo beam pattern form

$$B(\theta_m) = \frac{1}{\left|\vec{S}^H(\theta_m) \bullet \vec{U}_k^N\right|^2}$$

θ_m the pitch angle on the focal plane.

The beam pattern has pronounced maxima at the points where the denominator is zero (or very small) - and the is precisely the case when the angle θ_m of a Sources shows.

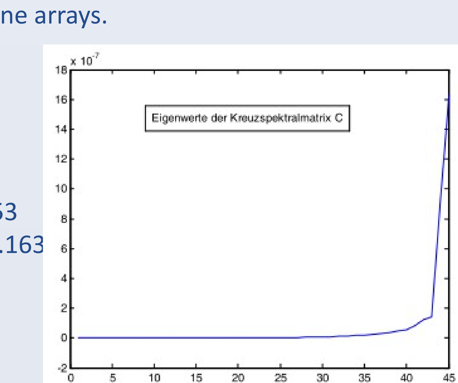
The height of the maxima has no reference the strength of the source.

Prerequisite for the process are here again uncorrelated sources. In reality, there are of course deviations from the ideal case:
- Not all noise eigenvalues are equal;
- The separation between the two subspaces is simply not possible, as no sharp transition exist between large and small eigenvalues.

The process provides the Inspector with regard to the noise Separation ability similar results as the Capon- Beamforming. Music algorithm works with regular and irregular microphone arrays.

Example:
The 8 largest eigenvalues at 2 speakers sources:

EW = 10-7 * (0.0034 0.0047 0.0053 0.0083 0.0125 0.0142 0.0916 0.163



The transition between the two large eigenvalues and the small eigenvalues to be seen clearly.

Capon algorithm

The Capon algorithm belongs to the class of adaptive Algorithms. He tries the direction of the incident Signal to appreciate as well. Capon beamforming tries, the signal power from other directions than the the source to be minimized. Ideally, this leads to a very narrow beam pattern and minimizes the effect of Sources of interference. The process is under ideal circumstances in able sources within the 3-dB width of the Delay + Sum beamforming separate.
A variational approach leads to the following form for the Beam Pattern

$$B(\theta_i) = \frac{1}{\vec{S}^H(\theta_i) \bullet C^{-1} \bullet \vec{S}(\theta_i)}$$

With the steering vectors $\vec{S}(\theta_i)$

and the inverse Spectral matrix of the microphone signals. C^{-1}

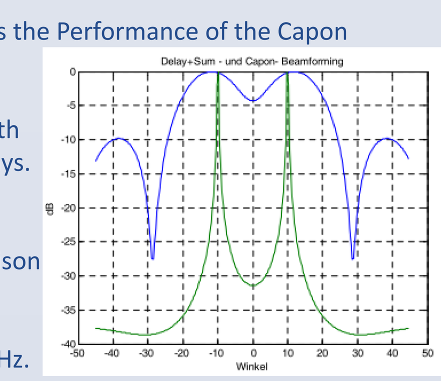
θ_i is the pitch angle on the focal plane.

The Spectral matrix is poorly correlated with sources conditioned and can no longer be readily Invert (regularization). Legalisation has also Influence on the absolute value of the estimated sound pressure (Peak height). This is not so reliable specify.

In contrast, the Delay and Sum Beamforming given by the beam pattern:

$$B_{DS}(\theta_i) = \vec{S}^H(\theta_i) \bullet C \bullet \vec{S}(\theta_i)$$

Unlike the D + S beamforming reduces the Performance of the Capon beamforming greatly in correlated sources and in bad SNR.
The Capon Beamforming can work with regular and irregular microphone arrays.



Example:
One-dimensional linear array comparison of D + S and Capon
Two point sources at + / - 10 °
and an evaluation frequency of 2000 Hz.

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