Assignment 5

Digital Signal Processing

AE4463P-23: Advanced Aircraft Noise

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Delft University of Technology

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by

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Style: TU Delft Report Style, with modifications by Daan Zwaneveld

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2D beamforming

Within this assignment the implementation and application of a 2D beamforming implementation will be explored. It will be utelised to investigate the source of sound for a flyover of a A 321. Similarly to the previous assignment, in which 1 dimensional beam forming was explored, an array of microphones will be utilised. However in contrary to the one dimensional procedure, the microphone array which is constructed for a 2D procedure forms a plane. By utilising a 2D-beamforming procedure it is possible to pinpoint the location of various sound sources, where the results can be analysed for various frequencies.

1.1. Microphone array

The microphone array which will be utilised within this assignment can observed in Figure 1.1. It can be seen that the array is characterised by a counter-clockwise outward spiral. The full microphone configuration fits within a circle with unit radius.

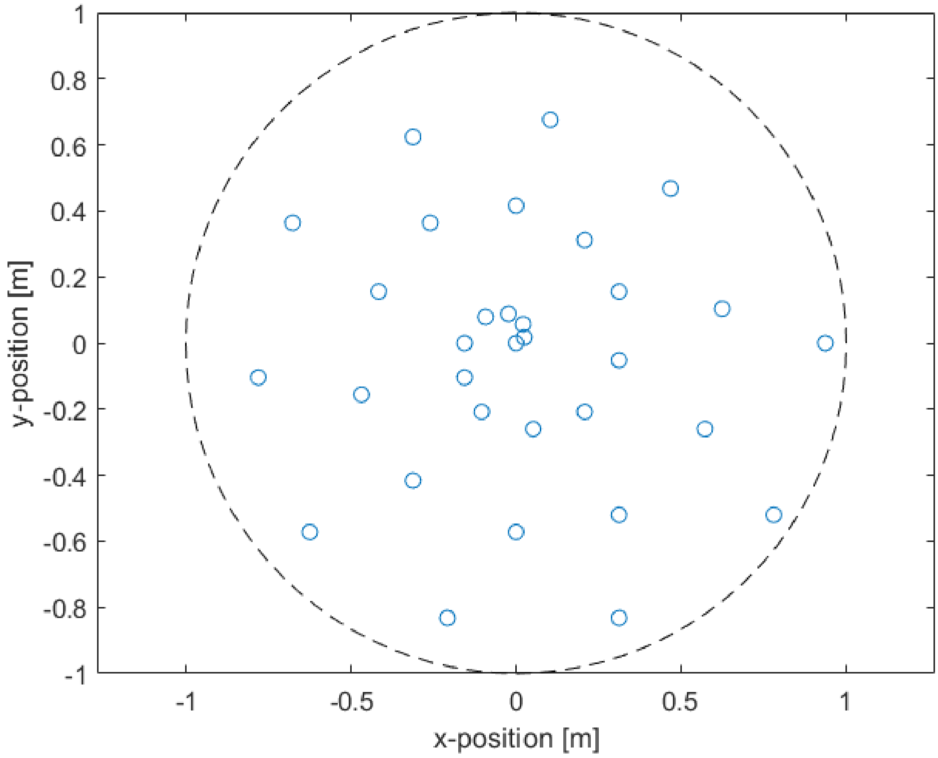


Figure 1.1: Configuration of the microphone array utilised

The array is constructed out of 32 microphones, where each microphone has a sampling frequency of 40 $[kHz]$. For each of the microphones pressure data is provided for 0.05 seconds at the mentioned sample frequency. Furthermore it should be noted that based on the sample frequency, the maximum observable frequency after Fourier transformation is 20 $[kHz]$.

1.2. Scanning Grid

The scanning grid is a vital part of the procedure discussed within this report. For each of the points within the grid a mathematical procedure will be utilised to determine the strength of sound on that grid point. After evaluation of all cells, it will be possible to analyse the sources of sound and the observed frequencies. As a results, its size will determine the observable space, and secondly the discretization utilised will determine the resolution.

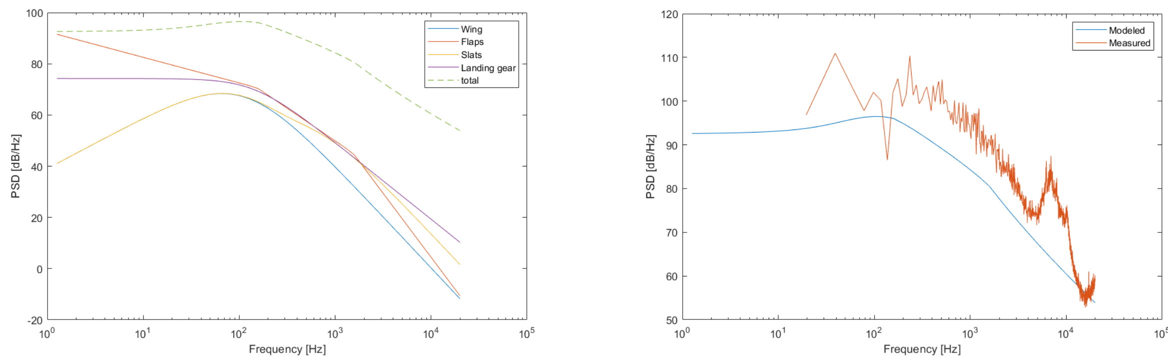
Based on recommendations within this assignment and from the professor it was chosen to create an asymmetric grid (50mx60m). This allows to more easily determine the horizontal and vertical components during analysis. The size utilised is sufficiently large to allow for full observation of the flyover. However it is not to large to results in computational difficulties when evaluating the full map. A resolution of 0.25 meters is utilised within the map, meaning that a total of around 50 000 points are evaluated.

Within MATLAB the grid is defined as follows

```
resolution = 0.25;  % [m]

X = -25:resolution:25;
Y = -30:resolution:30;

X_size = size(X,2);
Y_size = size(Y,2);

scanning_plane = zeros(Y_size, X_size);
```

1.3. Frequency band considered

Based on a sample frequency of 40 $[kHz]$, the maximum observable frequency can be computed to be 20 $[kHz]$. This range provides a large amount of frequencies which could potentially be analysed. From the assignment itself it could be concluded that the minimum frequency which should be analysed is 1.5 $[kHz]$ and the maximum is 9.5$[kHz]$. This range provided is still rather large, and when analysing the full band it will not be possible to pinpoint the various noise sources of the aircraft. However utilising the results found within assignment 3[1], where the air frame noise was analysed it is possible to put further limits on the frequency bands. Within Figure 1.2 the results found within the assignment can be observed.



(a) Airframe noise, seperated by components

(b) Comparison between measured and simulated data

Figure 1.2: Aircraft noise production expressed in power spectral density (PSD) vs frequency [1]

It was concluded that airframe noise is characterised by its low frequency contributions. While the engine is the main source of high frequency noise. Based on this figure and [2] the following based were considered. For airframe noise the band 1.5 kHz to 4.5 kHz was utilised while for the engines the band 4.5 kHz to 9.5 kHz was considered.

1.4. Beamforming Procedure

The formulation which is utilised to beamform the pressure data can be observed in Equation 1.1

$$B\left(\xi_j, f_k\right) = \frac{g^*\left(XX^*\right)g}{\|g\|} \tag{1.1}$$

Where g is steering vector / delay components, which is uniquely defined for each frequency (f_k) and point on the scanning grid (ξ_j). The steering vector contains values for each microphone, and is constructed for each pair of frequency and scanning point. For each of the microphones the distance to the scanning plane varies which is represented by $r_{n,j}$ with n indicating the location of the microphone and j indicating the location of the point on the scanning plane. Trough the use of the Pythagorean theorem in 3d it is possible to determine the distance r for all cases. Note the height (z) of the scanning plane with respect to the microphones is fixed at 64.87 $[m]$ and the speed of sound is 343 $[m/s]$.

$$g_n\left(\xi_j, f_k\right) = \frac{e^{-2\pi i f_k\left(\frac{r_{n,j}}{c}\right)}}{r_{n,j}} \tag{1.2}$$

$$r_{n,j} = \sqrt{(x_n - x'_j)^2 + (y_n - y'_j)^2 + (z)^2} \tag{1.3}$$

If the vector g (with size equal to the amount of microphones) is constructed it conjugate transpose can be readily be computed utilising the ”ctranspose” command within Matlab. The X values indicate the Fourier transforms for a certain frequency (f_k), here too the size is equal to the amount of microphones and the conjugate transpose can be computed in the same manner as for the steering vector. Within the formulation observed in Equation 1.1 the numerator should then results in one value which is then divided by the norm of g, to normalise the data.

Once this procedure has been performed, beamformed data will be available for each scanning point where each scanning point has data for all considered frequencies. Here lastly a form of incoherent averaging is performed to combine the effect of multiple frequencies instead of viewing singular select frequencies. This allows to view the sound levels within frequencies bands (more specifically the bands mentioned in section 1.3). The averaging is performed as follows:

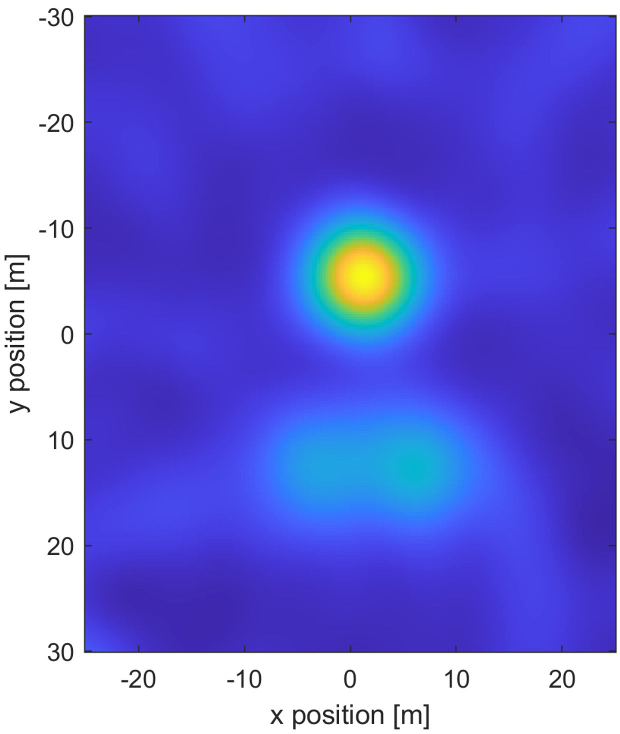
$$B_{incoh,avg}\left(\xi_j\right) = \frac{1}{N_f} \sum_{k=1}^{N_f} B\left(\xi_j, f_k\right) \tag{1.4}$$

Here the amount of frequencies which is being observed may be altered to suit the needs of analysis. N represent the amount of frequencies analysed within the band. For the low frequency band (1.5 kHz to 4.5 kHz) in this case the N is equal to 150 whereas for the high frequency band 4.5 kHz to 9 kHz) this value is 250.

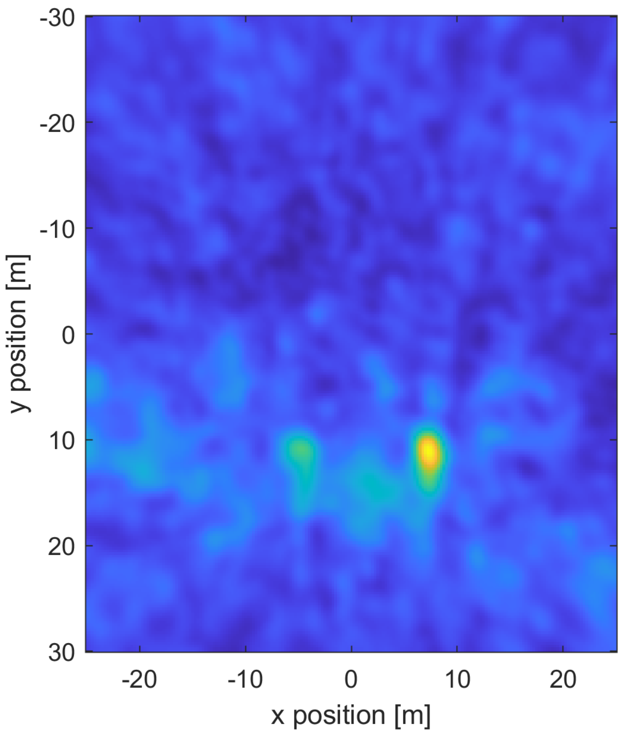
It was however found that, due to the averaging performed over the large amount of frequencies, that a the some noise was filtered out of the data. Due tho this the real sound was observed to be from more select distinct locations within the beamformed plots. This lightly deviated from the initial expectations, since it was expected that next to the key sources significant strength of sound was observable elsewhere whereas this was not the case.

1.5. Results

Plotting the averaged data over the previously mentioned bands the following results can be observed in Figure 1.3. Here the aircraft nose is located upward (into the negative y direction).



(a) Low frequency observations of the A321 flyover after beamforming



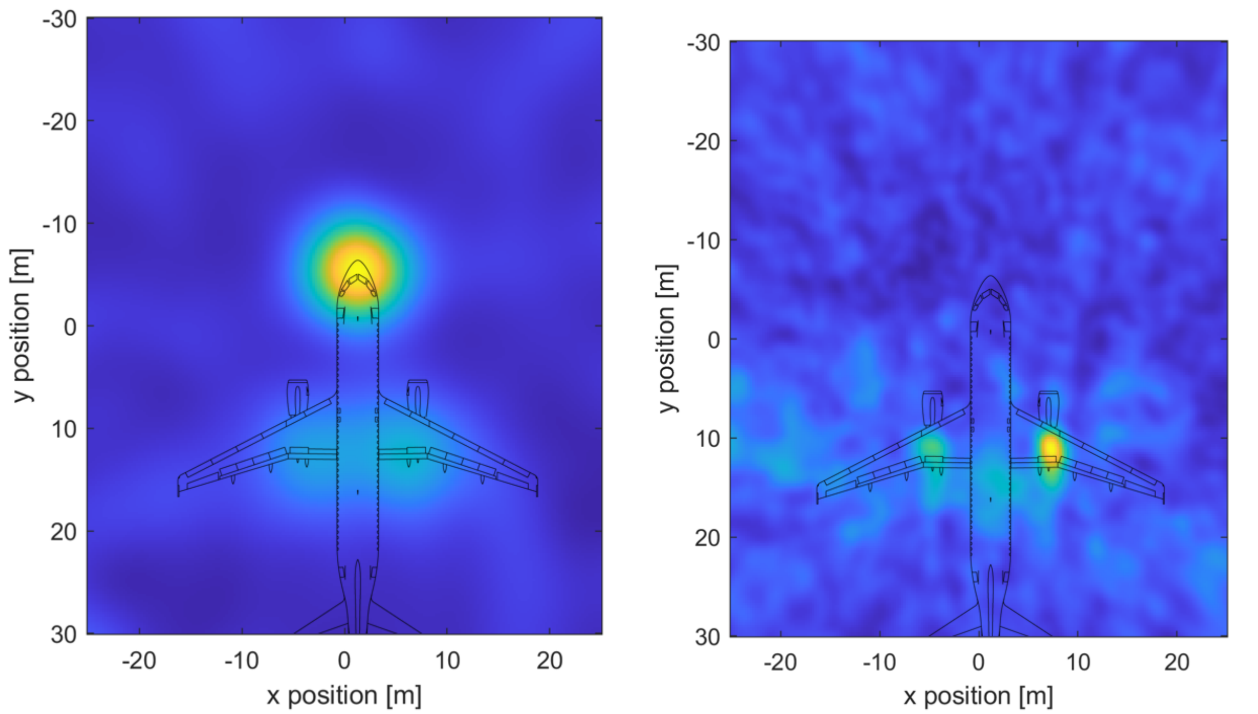
(b) High frequency observations of the A321 flyover after beamforming

Figure 1.3: A321 flyover with beamforming applied to pressure measurements taken with a microphone array, in a spiral configuration

On Figure 1.3a two key regions can be seen, one depicting the air-frame noise from main landing gear. While the second (although lower in strength) depicts the main landing gear. This main landing gear can be observed to be the lower bright blue colour within the figure. Whereas the nose gear is more yellow/ orange due to is higher strength. This behaviour is expected and coincides with the results obtained in simulation, since for lower frequencies is was determined that air frame noise is the most significant. Besides that, second to the slats the landing gear produced the most significant amount of noise. Therefore it can be concluded that likely the slats were not deployed within the currently made measurements. Furthermore comparing the location of the sources with the geometry of the A321 in Figure 1.4 it can be seen that the placement of the sound sources coincides with the location on the component of the aircraft.

Previously it was found that the engines are the most significant noise source at the higher frequencies. This was not determined trough simulation, but was extracted from performed measurements. Within Figure 1.3b, which was constructed taking only the higher frequencies into account it can be seen that two points or regions have a significant magnitude compared to there surroundings. Furthermore a small trail can be seen behind them. These are the two engines, there placement roughly coincides with the location of the main landing gear, which is the case for the A321. It can be seen that the right engines appears to be producing more sound in comparison to the left engine. Furthermore within the higher frequencies it can be seen that more noise variation exist within the figure, this could be explained due to the high frequency behaviour of wind/ turbulence.

Finally below in Figure 1.4 the results from Figure 1.3 can be observed again with the A321[1] contour superimposed onto the figure. It may be noticed that the aircraft flyover is not perfectly centred with respect to the x-position. And secondly the key noise from the engines located behind the engines.



(a) Low frequency observations of the A321 flyover after beamforming

(b) High frequency observations of the A321 flyover after beamforming

Figure 1.4: A321 flyover, with a321 contour superimposed onto beamformed measurements taken with a microphone array, in a spiral configuration.

[1] Julien.scavini, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

References

[1] Elisabeth Oosthoek Joshua Bogaert. *Assignment 3: Digital Signal Processing*. Dec. 2023.

[2] Prof. dr. ir. M. Snellen. *Principles of 2D beamforming and Imaging of aircraft noise*. 2024.

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Matlab code

```
% Assignment 5: Advanced Aircraft Noise

clear;
clc;

%% Import data from text file
% Script for importing data from the following text file:
%
%    filename: Array\Array.txt
%
% Auto-generated by MATLAB on 16-Feb-2024 14:20:26

% Set up the Import Options and import the data
opts = delimitedTextImportOptions("NumVariables", 3);

% Specify range and delimiter
opts.DataLines = [1, Inf];
opts.Delimiter = "\t";

% Specify column names and types
opts.VariableNames = ["VarName1", "VarName2", "VarName3"];
opts.VariableTypes = ["double", "double", "double"];

% Specify file level properties
opts.ExtraColumnsRule = "ignore";
opts.EmptyLineRule = "read";

% Import the data
Array = readtable("Array\Array.txt", opts);

% Convert to output type
Array = table2array(Array);

% Clear temporary variables
clear opts

load('Array\aircraft_noise_data_overhead_2020.mat');

h = 64.87;       % [m]
fs = 40000;      % [Hz]
n_mic = 32;      % [-]
c = 343;         % [m/s]

x_mic = Array(:,2);
y_mic = Array(:,3);

%% Main code

figure();
plot(x_mic, y_mic, "o");
xlabel("x-position [m]");
ylabel("y-position [m]");
hold on
axis equal

% add circle https://stackoverflow.com/a/29194105
```

```
rectangle('Position',[[0 0]-1 2 2],'Curvature',[1 1],'LineStyle','--');

resolution = 0.25;  % [m]

X = -25:resolution:25;
Y = -30:resolution:30;

X_size = size(X,2);
Y_size = size(Y,2);

scanning_plane = zeros(Y_size, X_size);

%%

microphone = 1;

T = 0.05;
N = length(p(microphone,:));
delta_t = T / N;
fs = 1 / delta_t;
delta_f = 1 / T;

fcf = [];

for microphone = 1:n_mic
    [S,F,T,P] = spectrogram(p(microphone,:), N, 0, N, fs, 'yaxis');
    fcf = [fcf; S.'];
end
% For every grid point, for every frequency

% gp_x = 1;
% gp_y = 1;
% k    = 10;

for x_plane = 1:X_size
    for y_plane = 1:Y_size

        disp([x_plane, y_plane]);

        inter = 0;

        % Select band to anlyse and make sure to also change the N factor
        % for averaging
        %for k = 76:226 % <--- activates low freq (landing gear)
        for k = 226:476 % <--- activates high freq (Engine)

            r = sqrt((x_mic - X(x_plane)).^2 + (y_mic - Y(y_plane)).^2 + h^2);
            g = exp(-2*pi*1i*F(k)*(r/c)) ./ r;
            g_ct = ctranspose(g);

            x_coef = fcf(:,k);
            x_coef_ct = ctranspose(x_coef);

            %inter = inter + g_ct*(x_coef*x_coef_ct)*g / (abs(g.')*abs(g));
            %inter = inter + g_ct*(x_coef*x_coef_ct)*g;
            %inter = inter + normalize(g_ct*(x_coef*x_coef_ct)*g) ;
            inter = inter + g_ct*(x_coef*x_coef_ct)*g / norm(g);

        end

        %inter = inter / (150);
        inter = inter / (250);

        scanning_plane(y_plane, x_plane) = inter;
    end
end

%%
figure();
imagesc(X, Y, abs(scanning_plane))
daspect([1 1 1])
```

```
xlabel("x position [m]")
ylabel("y position [m]")

% Enable to save figures to appropriate directory
% ax = gca;
% % Requires R2020a or later
% exportgraphics(ax,'Figures\HighFreq_compact.png','Resolution',300)
```