MEASUREMENT OF SOURCE DATA USING OPTIMISED BEAMFORMING TECHNIQUES ON MOVING SOURCES FOR OUTDOOR SOUND PROPAGATION MODELLING

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1 INTRODUCTION

This paper presents a novel beamforming measurement technique, successfully used to measure parts of the source directivity characteristics from operational helicopters. The modelling and prediction of noise levels at long range from elevated sources required an amalgamation of different approaches to capture the source data characteristics. These included optimisation of traditional methods along with novel beamforming techniques to fully characterise the directivity pattern in the propagation directions of interest. For example, measurement of some parts of the directivity pattern from the ground is not possible due to having to conduct them at long range to obtain the angle of interest. If the microphone is elevated to overcome the range problem, the source noise is corrupted by the ground reflection. This paper describes the techniques adopted and developed including the rationale behind their use. A large crane mounted beamforming array technique is described which was used to overcome the limitations of other measurement methods in the critical directivity direction, in the horizontal plane. The paper goes on to explore the possibility of exploiting this method to measure the noise from other elevated noise sources such as wind turbines.

2 APPLICATION

The application is key to determining the most relevant parts of the directivity pattern. Figure 1 below shows the typical flight profiles for helicopters. Knowledge of the receptor location of interest also enables the source data collection to be optimised. During transit, the receptor can be either at long range in the horizontal plane if the aircraft is at low altitude or can be below the aircraft if it is flying overhead at higher altitude. For the terrain and nap-of-the-earth (NOE) flight paths the receptor is most likely to be positioned in the horizontal plane of the helicopter directivity pattern.

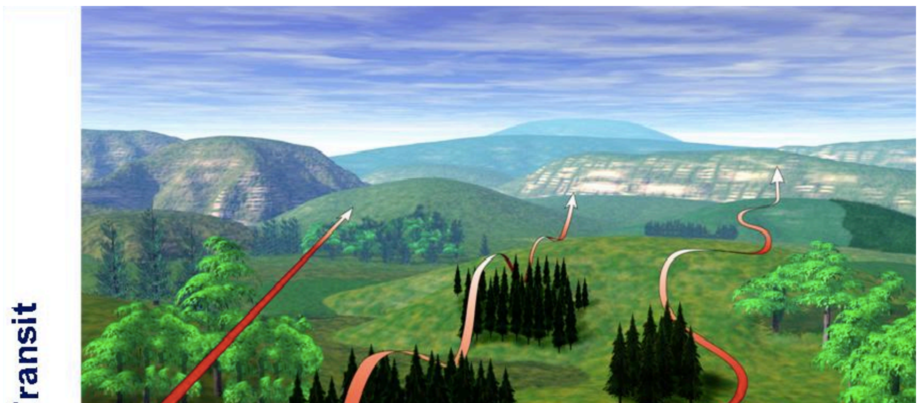


Figure 1, Typical training flight patterns.

The purpose of this work was to determine the source noise characteristics and directivity pattern of an elevated moving source, such as a helicopter, within a known set of tolerances. The best way to achieve this was to measure directly the directivity pattern for an operational helicopter over the range of conditions relevant to the requirements.

For an elevated aircraft moving at relatively high speed at variable heights above the ground the directivity pattern of interest is the lower hemispherical shell as shown in Figure 2 below. For ease of explanation, the co-ordinate system used is shown in Figure 3. This system was adopted since the angle phi (Φ) remains constant during a flyby at constant height and hence only theta (θ) is varying.

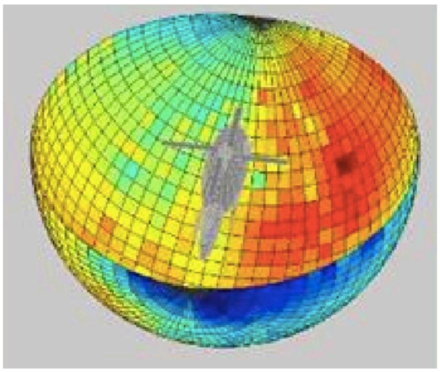


Figure 2, Helicopter directivity pattern

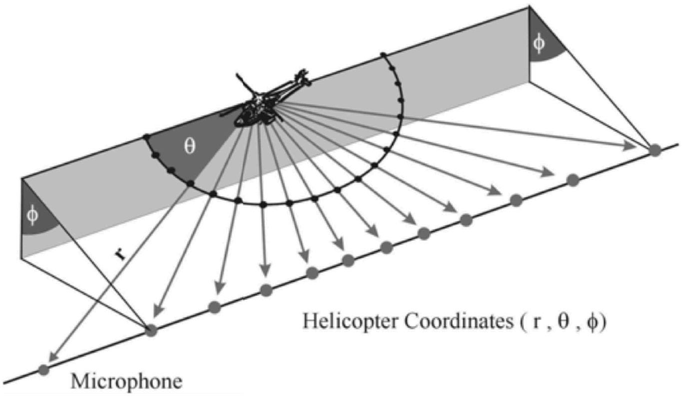


Figure 3, Directivity pattern coordinate system

The first step was to distill the source measurements down to quantifiable ways to measure. Criteria were determined in order to capture the source data within a known set of parameters, tolerances and constraints.

3 MEASUREMENT OF THE DIRECTIVITY PATTERN

Before embarking on the source measurement campaign, careful thought was required to understand the source, receptor, measurement environment, the level of tolerance and the frequency resolution of the analysis to ensure robust data was obtained.

3.1 Source region of measurement

There are two distinct acoustic regions around a source, the extent of each depends upon the size of the source. These are known as the acoustic near and far fields. The near field consists of contributions from all positions radiating from the source and can lead to large variations in measurements with small changes in the measurement position. In the far field the acoustic radiation decays according to linear acoustic theory and is more predictable in its propagation. The source data will be used to determine the noise level from the aircraft at long range in the far field. Therefore, unnecessary conversions from near to far field can be avoided if the source data is measured in the far field and then corrected back to 1m from the source. As a rule of thumb the far field is approximately 3 times the size of the radiating source. For a helicopter the dominant noise emanates from the main and tail rotors. The main rotors vary in size depending upon the aircraft and are in the range 15 to 30m. This places the far field in the region of 45 to 90m.

3.2 Frequency resolution

One of the fundamental requirements is for the 1/3 octave spectrum detail to be extracted down to 20Hz. For the spectral analysis at these low frequencies to be robust, a sufficiently long time sample in the directivity bin of interest has to be available for the analysis. A longer time sample can be obtained by moving further away from the source. A 3.5Hz narrow band frequency resolution is required to enable sufficient confidence in the spectral level in the 20Hz 1/3 octave bin. For the measurement sample to be long enough to perform the spectral analysis to the desired resolution, the source must remain within the 5° angular bin for at least 0.3s .

3.3 Microphone positions

For an aircraft flying above the reception point, the noise would emanate from below the aircraft and source measurements can be collected for this direction of propagation using ground plane mounted microphones. For an aircraft flying at low altitude at distance from the reception point, the noise from the aircraft would emanate close to the horizontal plane of the aircraft.

3.4 Meteorological conditions

The meteorological conditions are known to affect the propagation of sound through the atmosphere and refraction influences are apparent in wind speeds over 10 knots and at distances greater than 200m. To ensure the measurements are as devoid of meteorological effects as much as possible the conditions deemed conducive to valid measurements were in wind speeds below 10 knots where the propagation distance (in these non refracting conditions) can be extended to a range out to 500m without any significant adverse effects.

3.5 Frequency range

The human aural frequency range is most sensitive between 20Hz and 20kHz (Figure 4), outside of this range the perceived noise is rapidly attenuated. In the atmosphere, low frequencies propagate the furthest because the air absorption at these frequencies is small. In contrast, the frequencies above 10kHz are severely attenuated by air absorption over relatively short ranges and so are usually not dominant at the receiver even in strong refractive atmospheres (Figure 5).

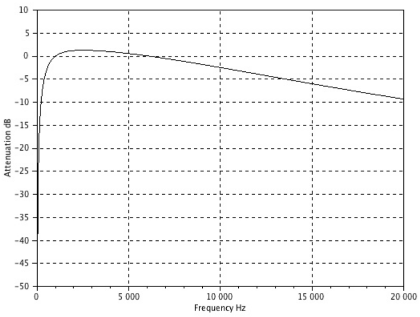


Figure 4, ‘A’ weighting attenuation

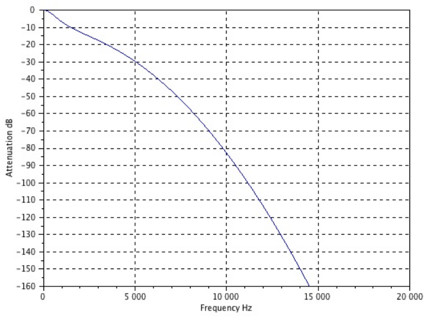


Figure 5, Air absorption at 1km range

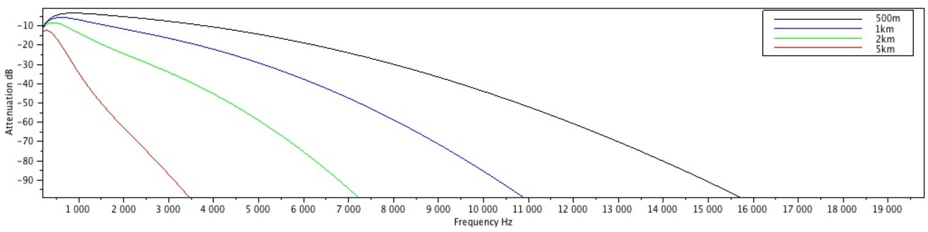


Figure 6, Combined ‘A’ weighting and air absorption at various ranges

When the attenuation effects of air absorption and ‘A’ weighting are combined with the geometric spreading, it is possible to determine the frequency range of interest based on the likely propagation range as shown in Figure 6. This shows that as the range increases, the lower frequencies become more dominant and the frequency band reduces. At 500m, the frequency band that dominates is between 200Hz and 3kHz. At 1km, this changes to 100Hz to 2kHz. At 2km, the dominant frequency range is 50Hz to 1kHz and at ranges greater than 5km, the frequency range is below 500Hz.

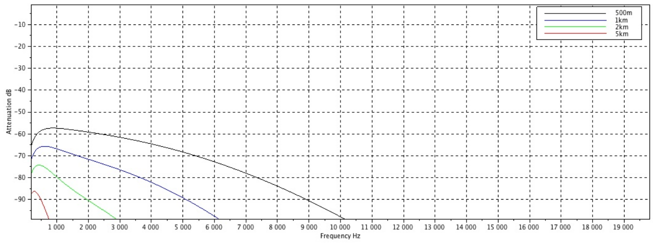


Figure 7, Inclusion of spherical spreading with air absorption and ‘A’ weighting

3.6 Spatial and temporal resolution

As the source of interest moves quickly, it is not possible to capture a long time sample of data for frequency analysis if measurements are too close. The resolution of the frequency spectrum is a function of the speed of the source (hover to 140knots) and the angular resolution required for the directivity pattern. The angular resolution for the directivity pattern was selected as 5° both in azimuth and elevation. This angular resolution limits the length of the time sample obtained in a particular directivity bin due to the speed of the source. The faster the source is moving the shorter the time window available in that angular bin for frequency analysis, see Table 1. A frequency resolution of 3.5Hz was selected and where more time was available within an angular bin the data were averaged over the same time window, improving the statistical confidence.

Angular and frequency resolution	40 knots (~20 ms^{-1})	120 knots (~60 ms^{-1})
Distance travelled in a 3.5Hz frequency bin (sample length ~0.3s)	5.8m	17.6m
Distance away from the aircraft to measure wholly within a 5° bin	67m	202m

Table 1; constraints which affect distance

In order to capture the full range of flight speeds at the chosen frequency resolution, the closest distance cannot be less than 200m. For the slower flight speeds valid data can be collected at closer than 200m but not less than the far field of approximately 90m.

At first sight the use of ground plane microphones would appear to be suitable. However, once you apply a set of constraints to the collection of the data to achieve the quality and tolerance strived for, it becomes apparent that the ground plane microphone on its own will not enable the whole directivity pattern to be collected.

The following tables 2 & 3, set out the constraints described above, along with the range of validity that was determined for each collection technique.

Measurement constraint	Distance of measurement
Far field	>90m from the source
Frequency resolution	>200m from source for 0.3s sample in a 5° angular bin
Meteorological conditions	<500m propagation in wind speeds less than 10 knots

Table 2; constraints which affect distance

Measurement position	Angular constraint
Ground plane	Limited to Phi angles of +- 60°
Tripod mounted	Not suitable due to ground reflection
Elevated	Not suitable due to ground reflection

Table 3; constraints which affect microphone position.

4 MEASUREMENT TECHNIQUES UTILISED

4.1 Ground based measurements

One way to overcome the reflection interference of elevated measurements, is by using ground mounted microphones. If the microphone is flush mounted in an infinite reflective baffle then this simply requires a -6dB pressure doubling correction across all frequency bands. Unfortunately the mounting of a microphone in a hard, infinite baffle is practically difficult and so a compromise between a predictable pressure doubling and realistically achievable mounting arrangements is required. This can be achieved either by use of a ground plane board, with space underneath to accommodate a flush mounted microphone or, more commonly due to ease of deployment, the microphone is laid on its side on the board or inverted a small distance above the board. The height of the microphone above the board limits the upper frequency at which pressure doubling occurs and is a compromise between a predictable correction and ease of deployment.

4.2 Elevated position measurements

It is not possible to obtain the whole directivity pattern of a helicopter using only ground mounted microphones due to the large distance required to obtain data in the horizontal plane (ϕ=90°), which is the most critical direction of interest for this application. One way of reducing the propagation distance and to obtain the phi measurements in the region of the horizontal plane is to elevate the microphone above the ground as shown in Figure 8 below.

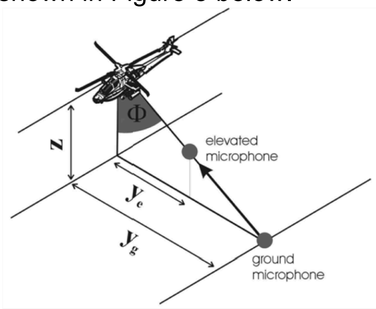


Figure 8, elevated microphones

This can be achieved by placing microphones on freestanding structures such as towers or cranes. Measuring the directivity pattern using elevated microphones means that ground reflection poses a problem. The diagram below illustrates this problem when trying to measure the direct wave in the region near to the horizontal plane of a helicopter. Experimental data was collected 220m from a hovering helicopter as shown in Figure 9 below. Figure 10 shows the spectrum measured using a single elevated microphone in the presence of a ground reflection, together with the predicted spectrum based on the main and tail rotor tones (from Figure 11).

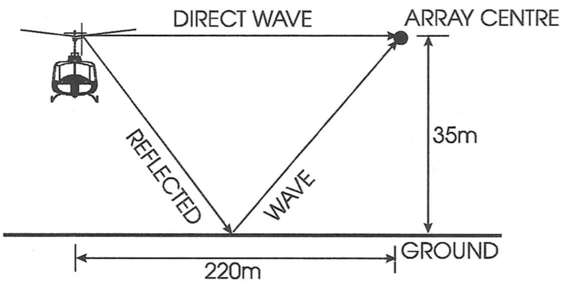
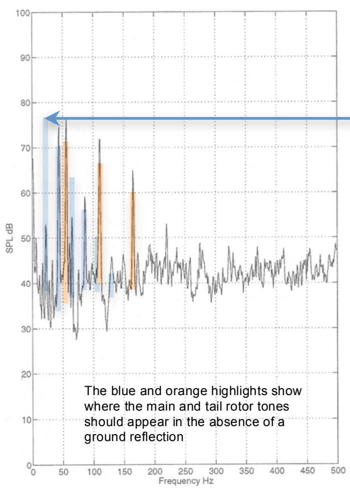


Figure 9, Ground reflection geometry



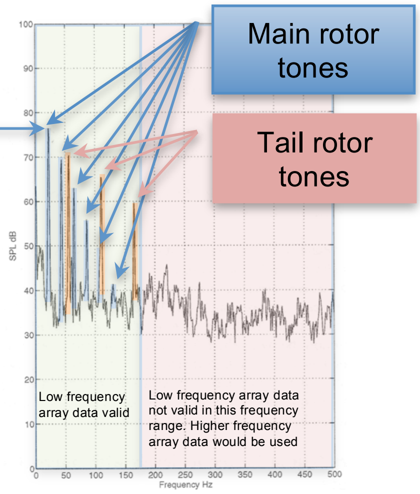


Figure 10, Single elevated microphone

Figure 11, Beamform array measurements

The spectral plot in Figure 11 shows as two overlapping harmonic series, the frequency of which is based on the number of blades and the speed of the rotors. The first series is generated by the main rotor and the second series by the tail rotor at a ratio of the main rotor, based on the fixed gearbox ratio. As can be seen from Figure 11, the main and tail rotor tones are expected to diminish in magnitude with increasing frequency (picked out in blue for the main rotor and orange for the tail rotor). Note that the fifth main rotor tone is almost the same frequency as the second tail rotor tone due to the ratio of the gearing between the two.

Whilst the single elevated microphone appears to randomly change the magnitude of the main and tail rotor tones, as shown in Figure 10, they can be explained by simple reflection theory. Each microphone in the beamform array is analysed as independent elevated microphones and then compared with reflection theory. The following results were measured and calculated.

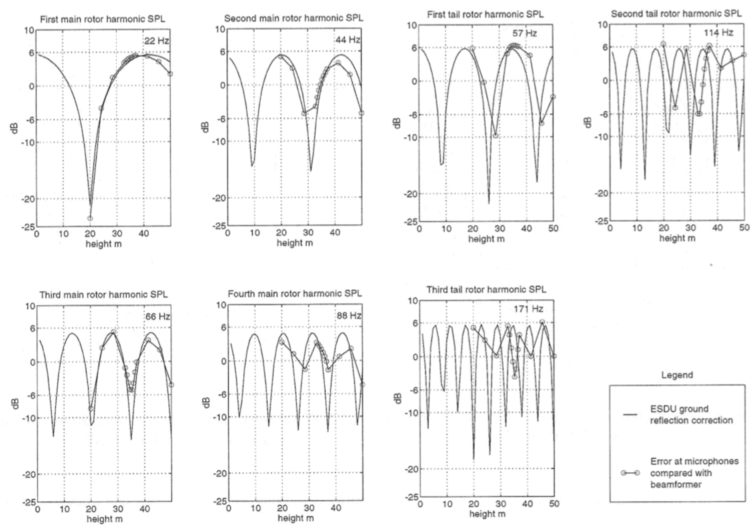


Figure 12, Elevated measurements compared to reflection theory

Figure 12 suggests that reflection theory could be used to remove the influence of the reflected wave from the measured signal to obtain the direct wave. However, when you examine the plots closely, the reflection dips become less correlated with the measurements as the frequency increases. Therefore the use of reflection corrections for single elevated microphones may be feasible for the low frequencies but even with accurate positional data derived from differential GPS, the discrepancy due to the errors associated with position are amplified at higher frequencies when the wavelength is much shorter and reflection correction becomes dubious. Therefore, for the purpose of measuring just the direct wave source characteristics, the constructive and destructive ground reflections are difficult to remove without very detailed information of the path length and also the complex ground reflection coefficient and the source data are likely to be under or over estimated using this technique.

A further complication of the interfering ground reflection is apparent when you consider the propagation time and direction of the emissions for a moving source, as shown in Figure 13 below. Not only are the emission angles of the direct and reflected waves different but the time of emission is too, all of which are difficult to correct for.

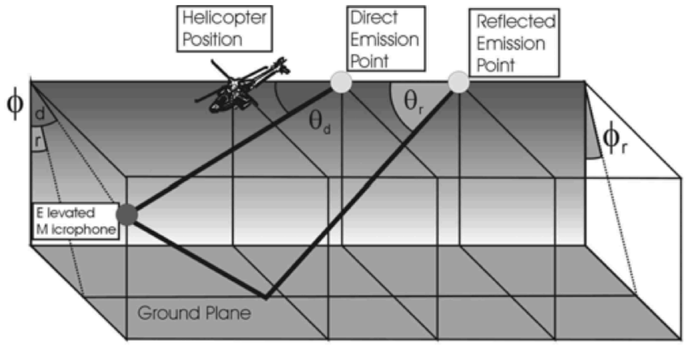


Figure 13, Refection geometry for a moving source.

5 THE SOLUTION DEVELOPED

The full measurement set up is shown in Figure 14 below. The directivity is obtained by flying by at a number of heights. Firstly at 35m AGL, which is the centre point of the beamforming arrays. This enables the primary vertical array to capture data for ϕ=±90 and θ 45° to 135°, along the sides of the hemisphere. The secondary array captures data on the nose and tail of the aircraft at ϕ =±90° and θ = 0° to 45° and 135° to 180°. The ground array fills in an area around the noise and tail underneath the horizontal plane in the range ϕ =0° to ±60° and θ = 0° to 45° and 135° to 180°. No data is captured beneath the aircraft at this flight height, since the time taken to sweep out 5° degrees at this range is too short. The flights are then repeated at a height of 200m. The ground array then captures data in the directivity hemisphere directly underneath and the beamform arrays can be steered to capture ϕ angles of 45° and 80°. The whole hemisphere is then derived from a 'patchwork quilt' of measurements from different heights and positions of microphone to derive the data within the tolerances, angles and frequency resolution defined for the data.

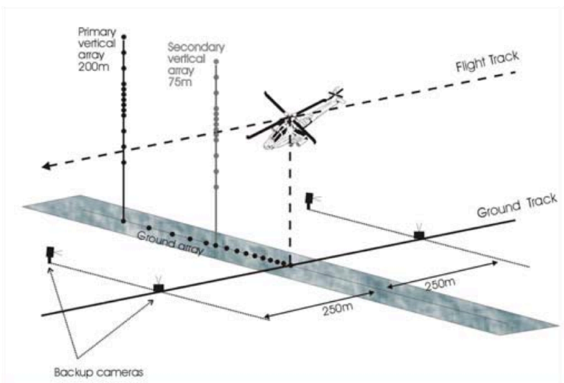


Figure 14; Full source directivity measurement set up.

5.1 Inverted ground plane microphones

Exploration of various options for the ground plane measurements established that for this application, a microphone inverted 2mm above the ground was the best compromise between pressure doubling over the required frequency range and the directivity response of the microphone. The first ground reflection dip for this setup occurs at approximately 8.5kHz. Whilst it would have been possible to use ground boards on soft ground, a larger surface such as a runway or road provides a much better reflective surface as shown in Figure 15 below.

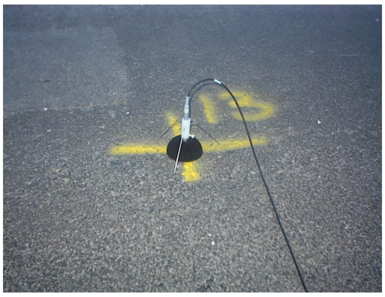


Figure 15, Inverted ground microphone

5.2 Elevated beamform array

For the elevated measurements, a beamform array solution was carefully designed to capture data in the horizontal plane over a wide frequency range, whilst minimising the effects of propagation due to meteorological effects and maximising the quality of the data.

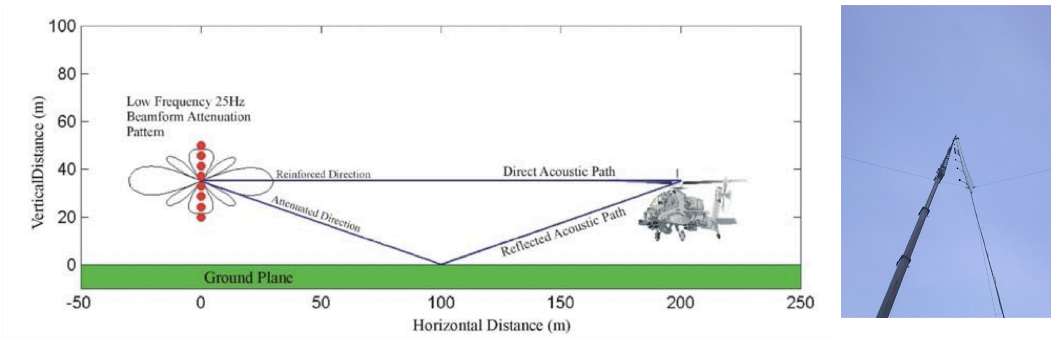


Figure 16, beamform array

After a number of laboratory tests, a design of the array was implemented based on two overlapping frequency ranges ‘A’ and ‘B’ by using 14 microphones configured to produce two 8 element arrays as shown in Figure 16. These enabled the frequency ranges of 20Hz to 160Hz and 160Hz to 1.6kHz to be determined as shown in Figures 17 and 18 below.

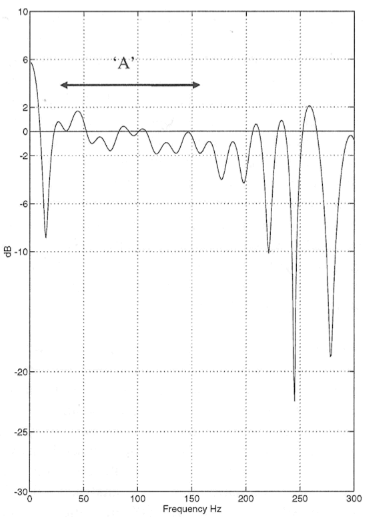


Figure 17, Low frequency array response

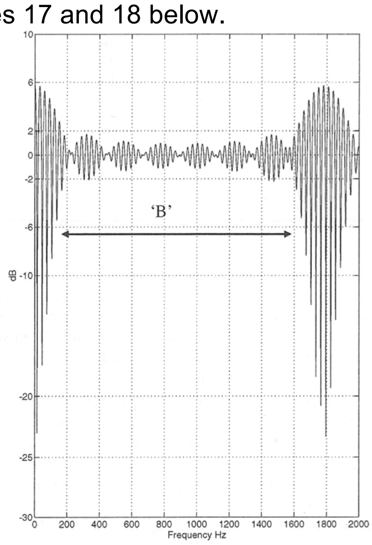


Figure 18, Higher frequency array response

6 OTHER APPLICATIONS

Another application which is similar to the one set out above, is that of noise from on and offshore wind farms. There are a number of factors in common, such as elevated sources, large source region and long range propagation in the horizontal plane. The major difference is that they are stationary and the source noise is a function of the windspeed and so the influence of the wind cannot be minimised for a particular turbine speed. The rotation of the wind turbine to face into the wind also simplifies the modeling since unlike the helicopter the orientation and the wind direction are always aligned.

The stationary nature of the wind turbine enables a longer time sample and hence frequency resolution to be obtained for the directivity pattern. Currently wind turbines are measured using ground based microphones and so do not capture the source noise in the direction of propagation in the horizontal plane. The application of a beamforming array to the problem would enable the directivity pattern to be measured for the whole range of azimuths and operational windspeeds.

7 REFERENCES

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