

Chapter 2

Acoustic Environment, Source Models and Sensor Arrays Theory

Abstract In the simplest form, a signal propagating from one point to another undergoes signal filtering from the propagation medium. Beamforming is a signal processing method to undo this filtering, such that the desired signal is retained at the receiver end, in addition to possibly suppression of unwanted signals. Hence, the underlying acoustic environment of the target application needs to be studied and modelled before a beamformer can be designed. This chapter discusses the fundamentals of acoustic environment modelling including different models for signal sources, propagation mediums and sensor arrays.

Keywords Acoustic modelling · Microphone array · Array geometry

2.1 Introduction

A signal propagating from one spatial location to another, where it is then observed, undergoes magnitude attenuation and time delay. This attenuation and time delay can be considered as filtering by the propagation medium. In the simplest form, a beamformer is usually used to undo or equalise this medium filtering such that the original signal can be extracted, with possibly further suppression of unwanted interferences and noise, as shown in Fig. 2.1. Of course, this concept can be easily extended to design advanced beamformers such as beamformers with steerable main beam and beamformers that works for both nearfield and farfield sources. Nevertheless, the design of beamformers consists of two parts: (a) modelling of acoustic environment and (b) designing the actual beamformers. This chapter provides the study for acoustic environment modelling, including the models for signal sources, propagation mediums and array geometries. All these models have direct influences in the design process of beamformer weights in the subsequent chapters.

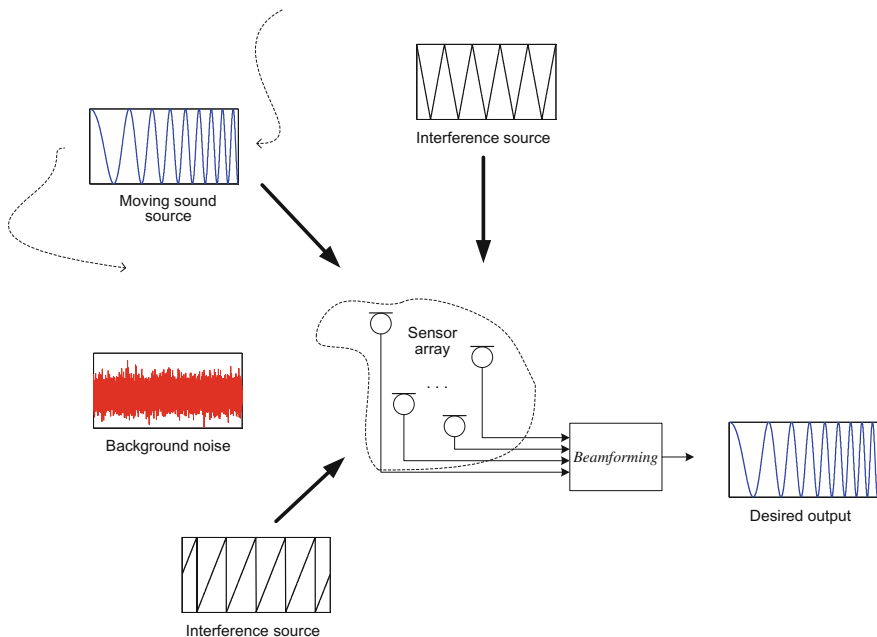


Fig. 2.1 General beamformer system

2.2 Environment and Channel Modelling

When a signal propagates from point A to point B in an open space, it is actually travelling through a complex time-dependent medium governed by its physical properties including temperature, viscosity, density, presence of foreign particles and much more. In fact, between point A and B, there is no guarantee that those physical quantities remain constant over time. The underlying mathematics becomes much more complicated when both points A and B are in an enclosed space with foreign objects, for example, an enclosed room with furnitures. In this case, the signal as observed at Point B not only consists of the direct propagation path from point A, but also the reflections from the wall of the enclosure as well as the scattering from the foreign objects in the enclosure. If the line of sight between A and B is obstructed, there will not be any direct path from A to B. From the signal processing point of view, each signal propagation path from point A to B can be modelled as separate, corresponding signal processing paths as shown in Fig. 2.2. The purpose of acoustic environment and channel modelling is to identify and characterise these paths in terms of transfer functions. Detailed acoustic environment and channel modelling can be found in [1, 2].

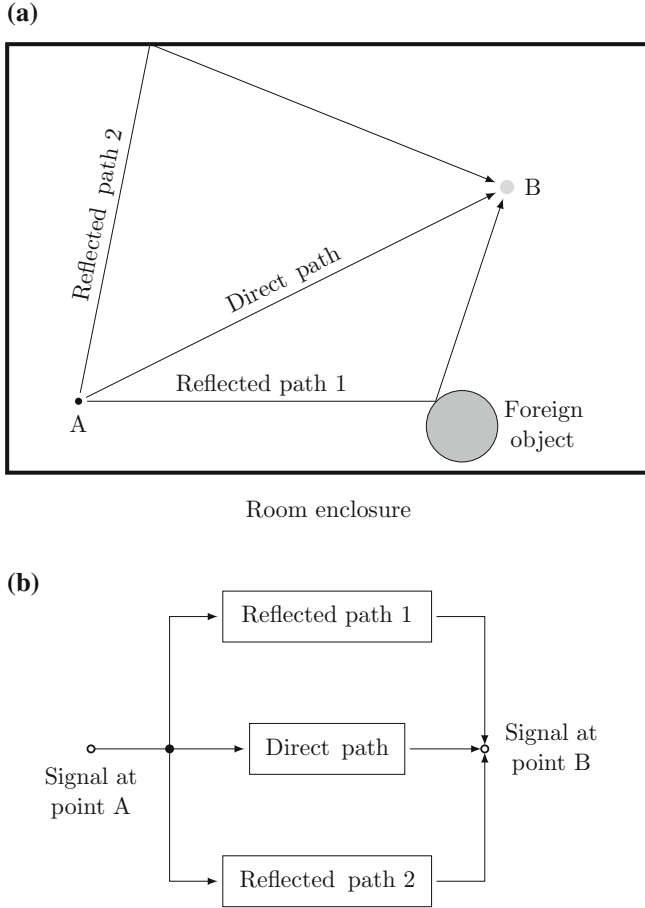


Fig. 2.2 Signal propagation through a medium. **a** Signal propagation in an enclosure. **b** Signal propagation block diagram

For the purpose of this book, an isotropic, homogeneous, non-dispersive, time-invariant propagation medium without any reflection nor reverberation is considered. Hence, the signal propagating from point A to B undergoes a linear, time-invariant (LTI) process as shown in Fig. 2.3. Signal as observed at any other points are also described by the same system. Mathematically, for a signal source represented in frequency domain as $S_0(\omega)$ and located at an arbitrary point $\mathbf{r}$ in space, the signal as observed at any point $\mathbf{r}_k$ is given by

$$X(\mathbf{r}_k, \omega) = A(\mathbf{r}, \mathbf{r}_k, \omega) S_0(\omega). \quad (2.1)$$

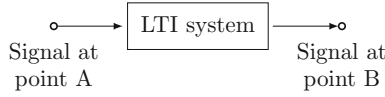


Fig. 2.3 Signal propagation in an isotropic, homogeneous, non-dispersive, time-invariant medium modelled as a LTI system

where $A(\cdot)$ is the transfer function describing the signal propagation from point $\mathbf{r}$ to point $\mathbf{r}_k$ in the modelled propagation medium, and $\omega = 2\pi f$, with f the frequency of the signal. In array signal processing, $A(\cdot)$ is also called array response. Note that (2.1) is only possible if the propagation medium is a LTI system or slowly time varying linear system. A more elaborate expression which includes solving the wave equations for a general propagation medium can be found in [3].

2.3 Source Models

A source is a physical device which generates energy, in this case sound energy, to be transmitted through a propagation medium. From signal processing point of view, it is the origin of an excitation in a system. In beamforming, the signal source needs to be appropriately modelled since its mathematical model forms part of the array response.

2.3.1 Distributed and Point Source

For an arbitrarily shaped signal source occupying a volume in space as shown in Fig. 2.4, the sound energy from the source will generate vibration on its surface. This vibration transmits the sound energy from the source's surface to the particles of the propagation medium that are in contact with the source surface. This sound energy or vibration will then propagate through the medium, which is normally indicated by pressure waves before they reach a receiver or sensor. The amount of energy transmitted from the source to the propagation medium depends on the intensity of the vibration on the source's surface and loss or dispersion of the medium. In general, the intensity is not uniformly distributed throughout the source's surface and the mathematical model for such source requires solving for complex wave equations [1, 3].

However, the mathematics can be simplified significantly if the physical size of the source is reduced to infinitesimally small, such that it only occupies a point in space. Due to its very small size, the sound intensity on its surface can be regarded as constant and its shape as a sphere. This source is called a point source and it has concentric, spherical wave fronts as shown in Fig. 2.5. Due to its much simpler

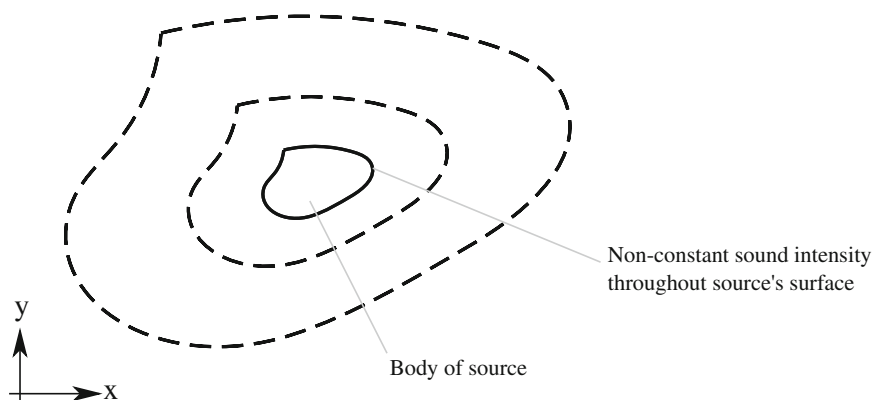


Fig. 2.4 Cross-sectional view of distributed source model

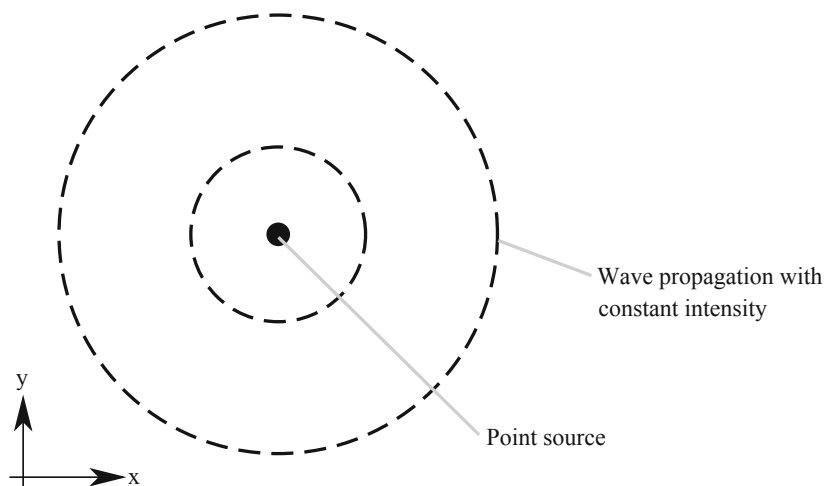


Fig. 2.5 Cross-sectional view of point source model

mathematical model, point source model is widely used in array signal processing. With the concept of point source, it is possible to model approximately a complex source by sampling its surface and treat each spatial point as a point source.

2.3.2 *Nearfield and Farfield Source*

For a point source located in space, the wave fronts that radiate outwards from it are spherical in shape. Hence, when signal observation is performed close to this signal source, such curvature in these wave fronts that impinge onto the observation

sensors need to be accounted for. Mathematically, for a point source propagating from a point $\mathbf{r} = (r, \phi)$ in cylindrical coordinate system, and travelling through a homogeneous, isotropic, non-dispersive and time-invariant medium (see Fig. 2.6), the signal received at a sensor (or receiver) is phase delayed and attenuated by its propagation response. This response, also known as array response or Green's function, is given by [4]

$$A(\mathbf{r}, \mathbf{r}_k, \omega) = \frac{1}{4\pi \|\mathbf{r}_k - \mathbf{r}\|} \exp\left(-j\frac{\omega}{c} \|\mathbf{r}_k - \mathbf{r}\|\right) \quad (2.2)$$

where $\mathbf{r}_k = (r_k, \phi_k)$ is the position of the k th sensor, and $\|\cdot\|$ denotes Cartesian distance. The attenuation in (2.2) is due to the decay of signal amplitude as it propagates outwards from its source. The constant 4π can be dropped for convenience since only the relative gain and phase difference between the sensors are important.

Although (2.2) gives a generic frequency response from an arbitrarily located signal source to an arbitrarily located sensor, the nonlinear Cartesian distance in the equation may complicate beamformer designs. A simplified source model can be obtained by considering the source to be at infinite distance away from the sensor array, i.e. $\|\mathbf{r}\| \rightarrow \infty$. The reason for this is that when the source is far enough from the sensor array, the wave front impinging on the array becomes planar (as opposed to spherical), which can simplify the propagation model. However, in this farfield

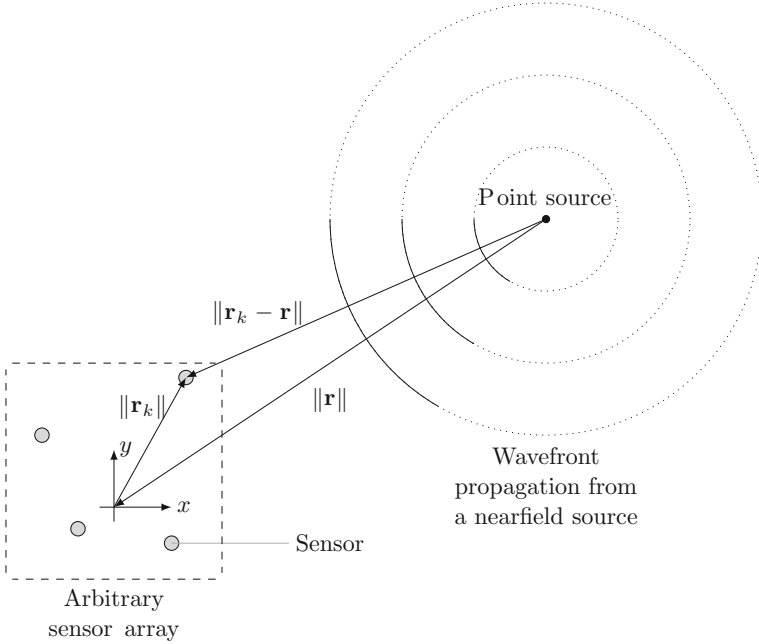


Fig. 2.6 Nearfield source model

source model, a reference point is required and is normally taken as the origin of the coordinate system or the centre of mass of the sensor array. The received signal at each sensor is then modelled relative to this reference point. For the reference point taken as the coordinate system's origin, the response of the k th sensor is then given by

$$A_0(\mathbf{r}, \mathbf{r}_k, \omega) = \frac{\|\mathbf{r}\|}{\|\mathbf{r}_k - \mathbf{r}\|} \exp\left(-j\frac{\omega}{c}(\|\mathbf{r}_k - \mathbf{r}\| - \|\mathbf{r}\|)\right). \quad (2.3)$$

Observe that as $\|\mathbf{r}\| \rightarrow \infty$,

$$\lim_{\|\mathbf{r}\| \rightarrow \infty} \frac{\|\mathbf{r}\|}{\|\mathbf{r}_k - \mathbf{r}\|} = 1 \quad (2.4)$$

and

$$\begin{aligned} \lim_{\|\mathbf{r}\| \rightarrow \infty} \|\mathbf{r}_k - \mathbf{r}\| - \|\mathbf{r}\| &= \|\mathbf{r}_k\| \cos(\phi_k - \phi) \\ &= \mathbf{r}_k \cdot \hat{\mathbf{r}} \end{aligned} \quad (2.5)$$

where $\hat{\mathbf{r}} = \frac{\mathbf{r}}{\|\mathbf{r}\|}$ is the unit vector or normalised source position. The array response for a farfield source is thus given by [4]

$$\begin{aligned} A_{far}(\mathbf{r}_k, \omega, \mathbf{r}) &= \lim_{\|\mathbf{r}\| \rightarrow \infty} A_0(\mathbf{r}_k, \omega, \mathbf{r}) \\ &= \exp\left(-j\frac{\omega}{c} \mathbf{r}_k \cdot \hat{\mathbf{r}}\right). \end{aligned} \quad (2.6)$$

For common array geometries such as uniform linear array and circular array (shown in Fig. 2.7), their farfield array responses are, respectively,

$$A_{lin}(\phi, k, \omega) = \exp\left(-j\frac{\omega}{c}kd \cos(\phi)\right) \quad (2.7)$$

$$A_{cir}(\phi, k, \omega) = \exp\left(-j\frac{\omega r_k}{c} \cos(\phi - \phi_k)\right). \quad (2.8)$$

Although farfield source model gives a simpler expression for the array response (c.f. (2.2) with (2.6)), the model is only valid for open space environment (e.g. free-field) and not for enclosed environment, such as small rooms due to the requirement $\|\mathbf{r}\| \rightarrow \infty$. However, studies have shown that in practice, $\|\mathbf{r}\| \rightarrow \infty$ is not a strict requirement for (2.6) to be valid. For example, Eq. (2.6) may still be valid for medium-sized office and indoor stadium, depending on the array size. One of the widely used quantitative lower bounds as a practical criterion for the farfield source model to be valid is [5–7]

$$r > \frac{2L_a^2}{\lambda} \quad (2.9)$$

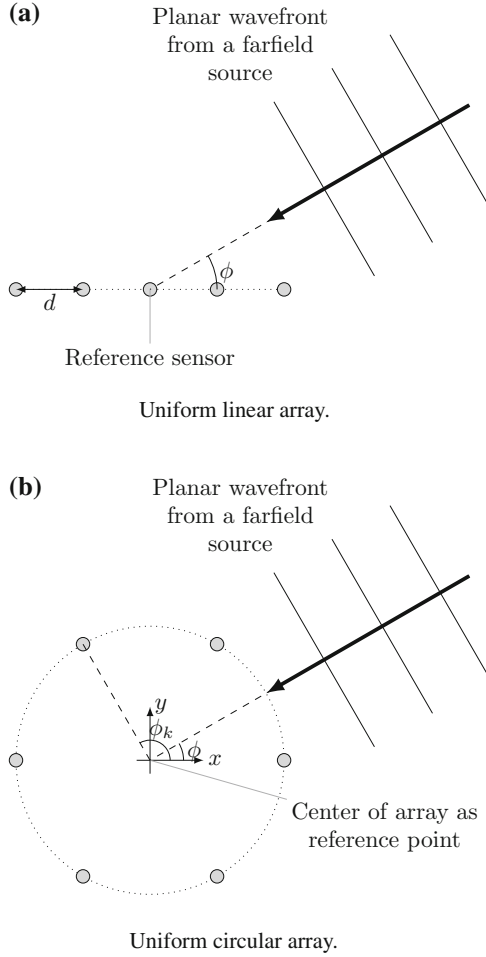


Fig. 2.7 Farfield source model for uniform **a** linear and **b** circular arrays

where $r = \|\mathbf{r}\|$, L_a is the largest array aperture size and λ is the operating signal's wavelength. This criterion is based on the acceptable quadratic phase error and its detailed discussion can be found in [8–11]. Due to the simplicity of farfield source model, various nearfield beamforming solutions are derived from this model, such as radial transformation [4], nearfield compensation [5], and radial reciprocity method [12].

2.4 Sensor Arrays Theory

Sensors placed in space play the role of sampling received signal in space. This spatial sampling is similar to temporal sampling in digital signal processing (DSP) systems. Therefore, the sensors must be well distributed in space such that sufficient spatial information can be captured from the spatial sampling of the received signal. At the same time, the spacing of the sensors is required to be less than half the wavelengths of the received signals to avoid spatial aliasing. Generally, spatial discrimination capability depends on array aperture size, i.e. as aperture size increase, discrimination improves. The absolute aperture size is not important, rather its size relative to the wavelengths of the received signals is critical. However, the aperture size is normally restricted due to practical reasons such as cost and design decision. There is no single golden rule on the placement of sensors, and the placement choice is entirely application specific.

2.4.1 Spatial Aliasing

In beamforming or spatial filtering, sensors placed in space play the role of spatially sampling the received wave. Hence, similar to Nyquist criterion in temporal sampling, the smallest distance d between adjacent sensors must be [13]

$$d \leq \frac{\lambda}{2} \quad (2.10)$$

in order to avoid spatial aliasing. The wavelength λ and frequency f of a signal are related by

$$c = f\lambda \quad (2.11)$$

where the constant c is the signal propagation speed (e.g. $c = 343\text{ms}^{-1}$ for air in room temperature and pressure). Criterion (2.10) is a necessary condition for narrowband beamformers to avoid spatial aliasing. As an example, consider an endfire linear array with 6 elements and its inter-element spacing of 4 cm. The highest signal frequency that it can resolve before spatial aliasing occurs is $f_{\max} \approx 4.3$ kHz. The beam patterns of a weight-and-sum beamformer designed for frequency $f = 3$ kHz and 7 kHz using this array are shown in Fig. 2.8. The figure clearly demonstrates the occurrence of spatial aliasing when (2.10) is violated. For broadband beamformers, the wavelength λ is chosen to be the smallest signal wavelength, which corresponds to the highest frequency component in a broadband signal. This selection guarantees no spatial aliasing for all frequencies up to the chosen frequency [14].

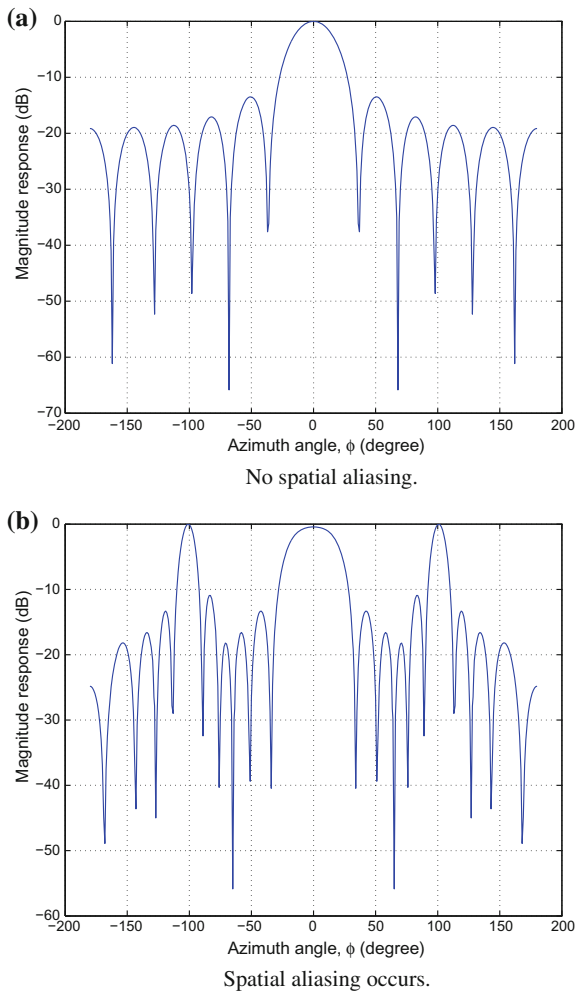


Fig. 2.8 Endfire linear array with inter-element spacing of 4 cm for **a** without and **b** with spatial aliasing

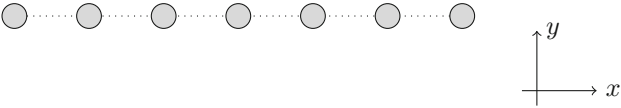


Fig. 2.9 Example of one-dimensional array

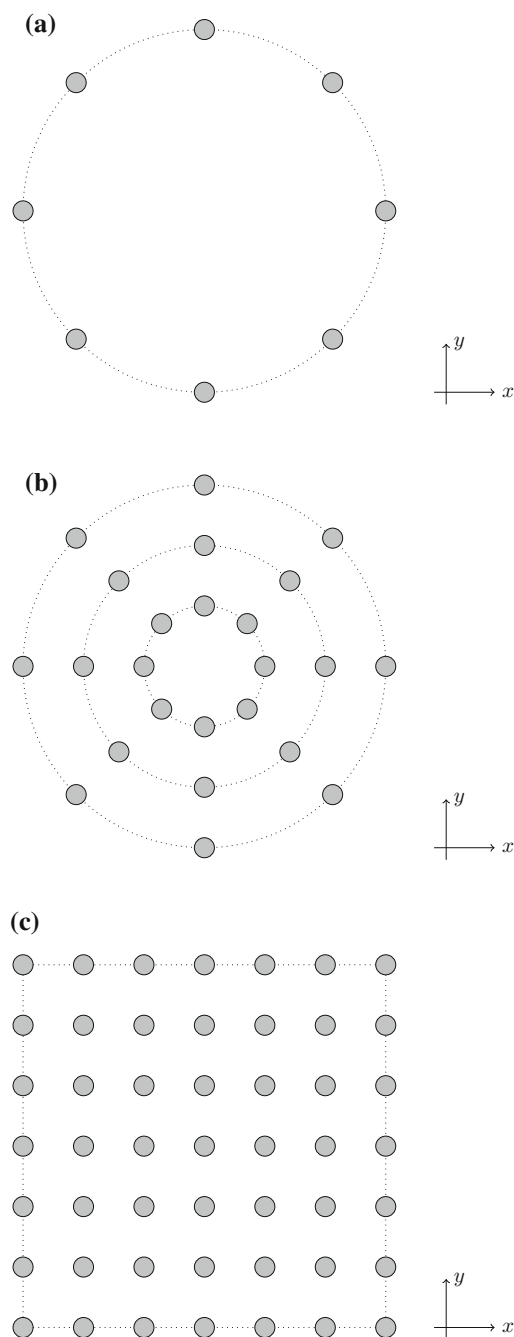


Fig. 2.10 Examples of two-dimensional arrays. **a** Circular array **b** Concentric circular array **c** Rectangular planar array

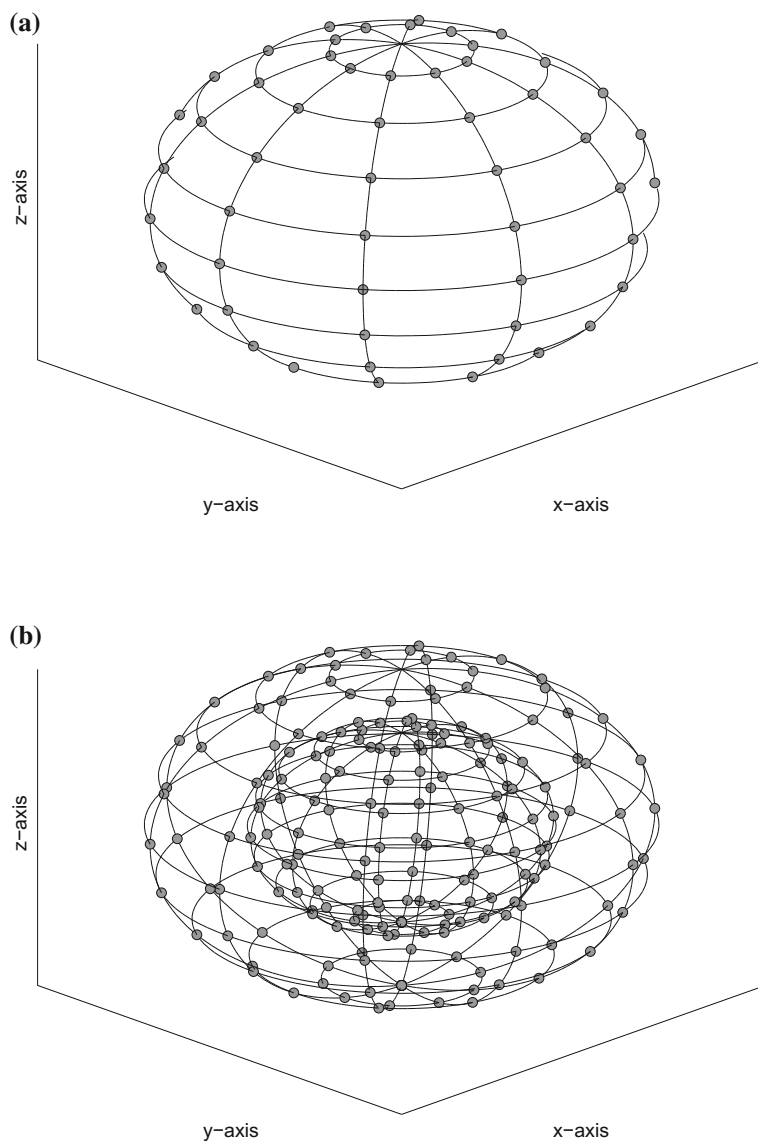


Fig. 2.11 Examples of three-dimensional arrays. **a** Spherical surface array. **b** Spherical volume array

2.4.2 Array Geometry

The placement of sensors in space to form a sensor array is dependent on design requirements, which include the number of sensors, the size of the array relative to the operating frequency and the performance of the array. The sensors can either be placed arbitrarily or follow a known geometry shape. Regardless, the choice of array geometry is important in beamformer designs as it plays a major role in the performance of the beamformers. This is because different array geometries have different advantages and limitations [15, 16]. For example, a uniform linear array (see Fig. 2.9) has the best spatial resolution either at broadside or endfire, depending on the target application, whereas a uniform circular array (see Fig. 2.10a) has a uniform spatial resolution for the whole azimuth range.

In general, array geometries can be categorised into three main categories, namely one-dimensional, two-dimensional and three-dimensional arrays. One-dimensional arrays comprise of placing sensors in a line as shown in Fig. 2.9. Its variants include uniformly or non-uniformly spaced array elements, and broadside or endfire configuration types. Two-dimensional arrays consist of placing sensors on a plane, which can either fill up an enclosed area or along its perimeter. Common two-dimensional arrays include planar, circular and multiring concentric circular arrays as shown in Fig. 2.10. In the case of three-dimensional arrays, the sensors can be placed on the surface of three-dimensional solids, or they can be placed on frames to fill up the volume of three-dimensional solids, such as cylinder or sphere (see Fig. 2.11). The choice of array patterns depends heavily on the target applications, and some interesting array geometries specific to their applications can be found in [17–19].

2.5 Spiral Arm Array Geometry

The array geometry that is used extensively to illustrate beamformer design formulations in the following chapters is a modified concentric circular array as shown in Fig. 2.12. This array geometry can be called spiral arm array since its sensors are extending spirally outwards from its centre. It consists of K_{ring} concentric rings, indexed by $k_{ring} = 0, \dots, K_{ring} - 1$, with K_{sen} sensors, indexed by $k_{sen} = 0, \dots, K_{sen} - 1$, uniformly spaced along the circumference of each ring. The k_{ring}^{th} ring is further twisted by an angle $\phi_{k_{ring}}$. Hence, the total number of sensors for such array is $K = K_{ring}K_{sen}$, and each sensor can also be indexed by $k = (k_{ring} - 1)K_{sen} + k_{sen}$.

The positions (in cylindrical coordinate system) of the sensors are given by

$$\mathbf{r}_k = \left(r_{k_{ring}}, \frac{2\pi k_{sen}}{K_{sen}} + \phi_{k_{ring}} \right) \quad (2.12)$$

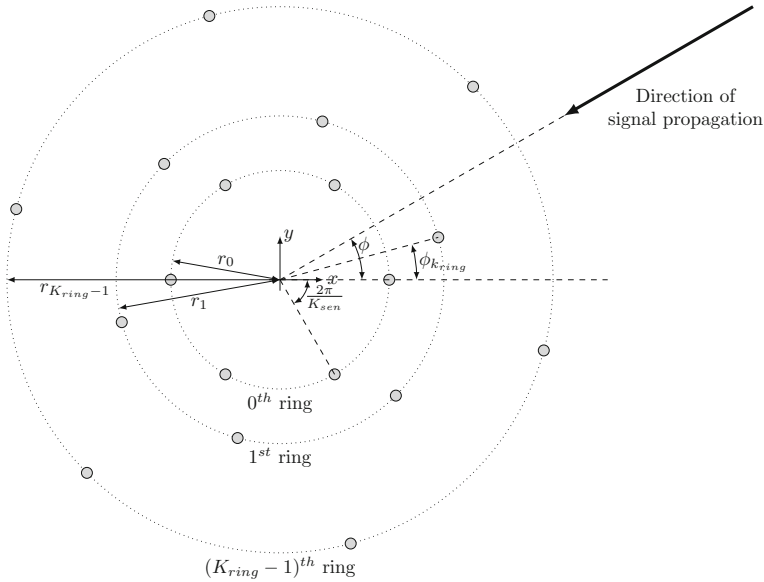


Fig. 2.12 Proposed spiral arm array geometry

where the centre of the array is taken as the origin of the coordinate system. The ring radii $r_{k_{ring}}$ and the twist angle $\phi_{k_{ring}}$ are design parameters. Its array response (with the centre of array taken as the reference point) to a farfield source impinging the array from azimuth angle ϕ is given by

$$A_{far}(\mathbf{r}, \mathbf{r}_k, \omega) = \exp\left(-j\frac{\omega r_{k_{ring}}}{c} \cos\left(\phi - \frac{2\pi k_{sen}}{K_{sen}} - \phi_{k_{ring}}\right)\right). \quad (2.13)$$

This spiral arm array geometry possesses a few desirable characteristics that make it an attractive candidate for broadband beamforming. Firstly, its multiring nature allows each ring to compensate for separate frequency bands in a cooperative manner to achieve larger bandwidth for broadband beamforming [20]. Besides, since it is a two-dimensional array, it provides full 360° coverage of the azimuthal dimension, without any ambiguity (as opposed to linear array).

Secondly, its circular symmetry property means that it has uniform resolution throughout the entire azimuthal dimension [15]. This allows the beamformer to have a response that is symmetric about its look direction. Moreover, the circular symmetry property can be exploited in the design of steerable beamformer to provide full 360° beam steering (see Sect. 4.5).

Thirdly, each ring of the spiral arm array geometry has undergone a slight twist (c.f. Fig. 2.10b). This rotation introduces irregularity and reduces the periodicity in its geometry, thus providing irregular spatial sampling of the received signals, which

can help to suppress spatial aliasing [19, 21]. This property is useful in broadband beamformer designs, especially with limited number of sensor, due to conflicting array aperture size requirements, i.e. the spacing between sensors need to be small enough to avoid spatial aliasing for high-frequency components but large enough to maintain directivity for low-frequency components.

2.5.1 Ring Radii

One of the design parameters for the spiral arm array is its ring radii. From Nyquist sampling theorem (2.10), the spacing between adjacent sensors must not be larger than half the wavelength of the highest operating frequency in order to avoid spatial aliasing. In contrast, the array aperture need to be sufficiently large to provide the required spatial resolution for the low-frequency components. In order to satisfy these contrasting requirements, the concept of narrowband signal processing is employed, where each concentric ring from the proposed spiral arm array is designed to handle a single-frequency component. Under this scheme, each ring radius is then selected to satisfy the Nyquist criterion for its corresponding operating frequency given by

$$r_{k_{ring}} \leq \frac{c}{4f_{k_{ring}} \sin\left(\frac{\pi}{K_{ring}}\right)} \quad (2.14)$$

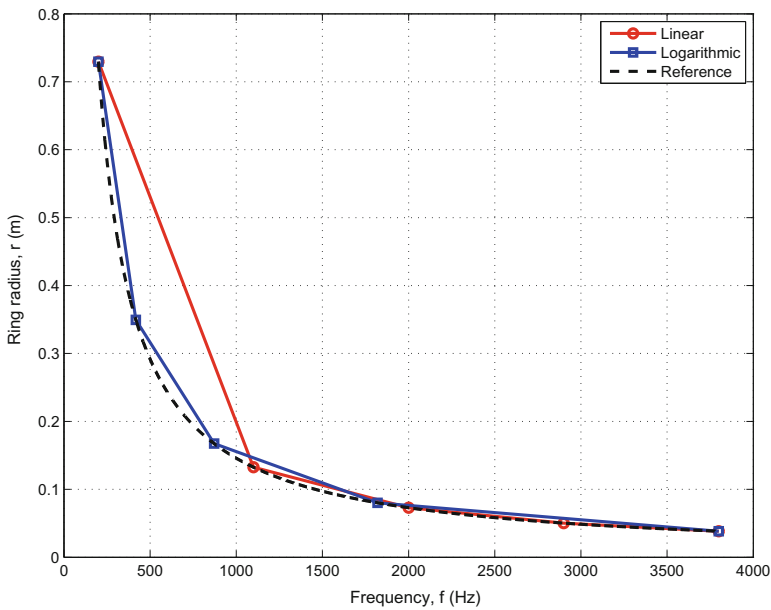


Fig. 2.13 Discretisation of ring radii

where $f_{k_{ring}} \in \Omega$ is the maximum operating frequency for the k_{ring}^{th} ring, and Ω is the spectral range of interest. As an example, for $\Omega = [0.20, 3.8]$ kHz and $K_{ring} = 5$, one possible choice (following linear discretisation) is $f_0 = 3.8$ kHz, $f_1 = 2.9$ kHz, $f_2 = 2.0$ kHz, $f_3 = 1.1$ Hz and $f_4 = 0.2$ kHz.

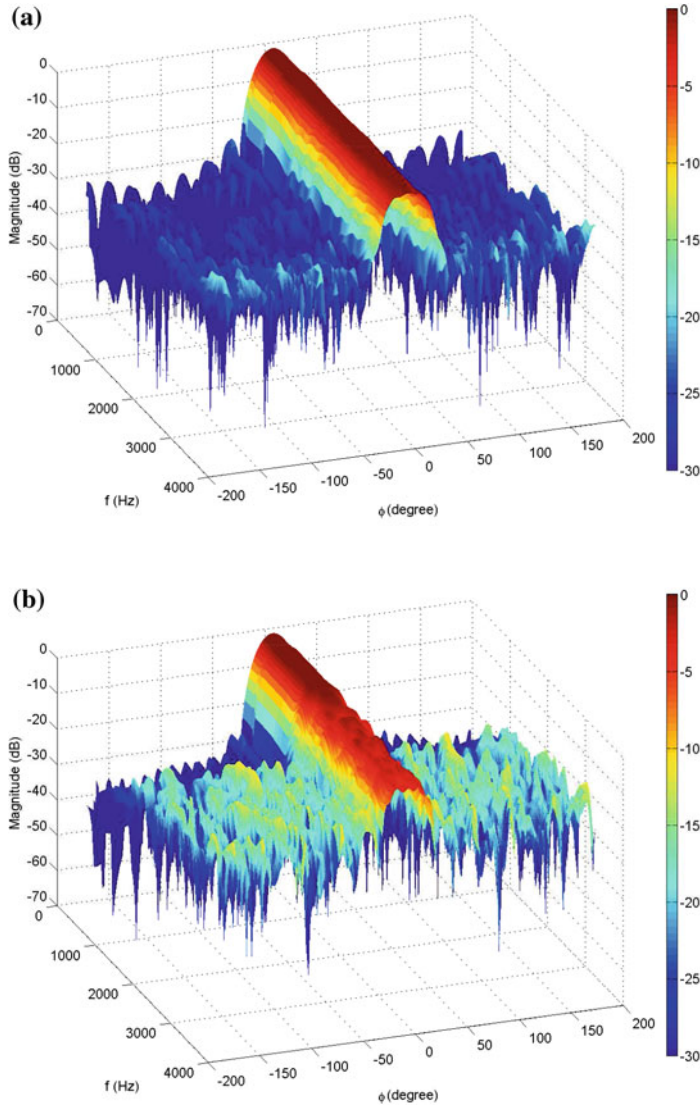


Fig. 2.14 Beampatterns for fixed beamformer using **a** logarithmic and **b** linear discretisation of ring radii

Table 2.1 Design parameters for fixed beamformer to illustrate different ring radii discretisation

Design parameters	Value
Number of rings, K_{ring}	5
Number of sensors per ring, K_{sen}	5
Ring twist angle, $\phi_{k_{ring}}$	0°
Sampling frequency, f_s	8 kHz
Spectral range, Ω	[0.2, 3.8] kHz
Spatial pass region, Φ_{pb}	$ \phi \leq 15^\circ$
Spatial stop region, Φ_{sb}	$ \phi \geq 25^\circ$
FIR filter length, N	64
Speed of propagating wave, c	343 m/s

However, with the finite number of rings covering a broadband signal, equation (2.14) results in the discretisation of the broadband frequency range into K_{ring} bands. Judging from (2.14), which involves an inverse relationship between $r_{k_{ring}}$ and $f_{k_{ring}}$, the logarithmic discretisation of $f_{k_{ring}}$ will outperform the linear discretisation. This is because the uniform step size in linear discretisation does not provide sufficient resolution at low frequencies where the value of the function (2.14) changes more rapidly than at high frequencies. On the other hand, the logarithmic discretisation with non-uniform step size fits nicely for (2.14), both at low and high frequencies.

This observation is shown in Fig. 2.13, where

$$r_{k_{ring}} = \frac{c}{4f_{k_{ring}} \sin\left(\frac{\pi}{K_{ring}}\right)} \quad (2.15)$$

for $f_{k_{ring}} \in [0.2, 3.8]$ kHz (the reference) is discretised into $K_{ring} = 5$ bands using both linear and logarithmic discretisation schemes. To further highlight this observation, the beampatterns for a fixed beamformer with linear and logarithmic ring radii sampling are shown in Fig. 2.14. The beamformers are designed using the weighted LS formulation in Sect. 3.3.1 with the parameters in Table 2.1, and $r_{k_{ring}} = \{0.0319, 0.0666, 0.1391, 0.2904, 0.6063\}$ m for linear discretisation and $r_{k_{ring}} = \{0.0319, 0.0418, 0.0606, 0.1102, 0.6063\}$ m for logarithmic discretisation.

2.5.2 Twist Angle

Unfortunately, the selection of the ring twist angle is not as straightforward as for the ring radii. The amount of twist for each ring can be different and independent of one another. However, if $\phi_{k_{ring}}$ is a multiple of $\frac{2\pi}{K_{ring}}$, then the spiral arm array will be similar to the array in Fig. 2.10b.

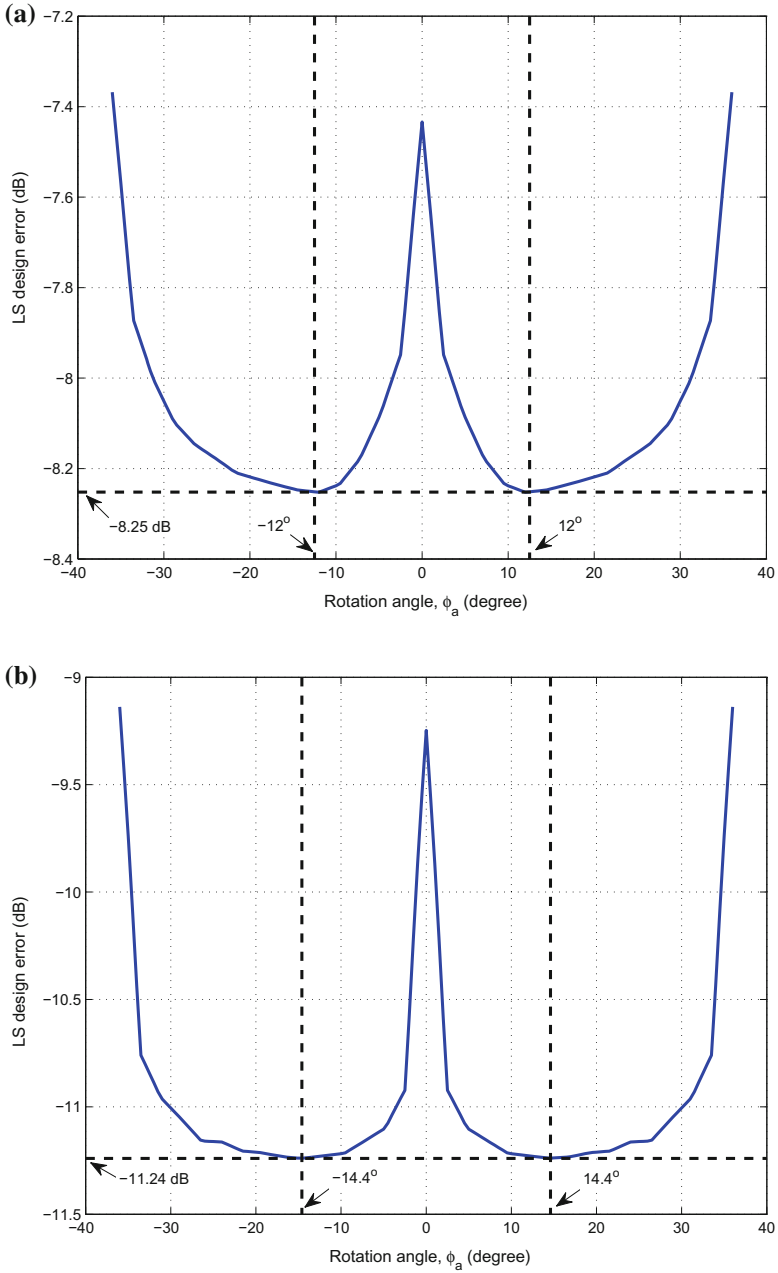


Fig. 2.15 Plot of weighted LS design errors versus ϕ_a for **a** $K_{ring} = 4$ and **b** $K_{ring} = 5$

In order to simplify the selection of $\phi_{k_{ring}}$, each ring twist is restricted to be a multiple of a scalar twist ϕ_a , i.e.

$$\phi_{k_{ring}} = k_{ring} \phi_a. \quad (2.16)$$

Then, a simple line search algorithm can be used to find the optimum candidate for ϕ_a , which is highly dependent on the overall beamformer design formulation and specification. Figure 2.15 shows the cost (3.63) for the weighted LS farfield-only steerable beamformer designs in Chap. 4 with $\phi_a \in [-36^\circ, 36^\circ]$ for $K_{ring} = 4$ and 5. Other design parameters are as given in Tables 4.1. From Fig. 2.15 and due to the circular symmetry of the spiral arm array, the optimum values for $K_{ring} = 4$ is $\phi_a = \pm \left(12^\circ + \frac{180^\circ z}{K_{sen}}\right)$ and for $K_{ring} = 5$ is $\phi_a = \pm \left(14.4^\circ + \frac{180^\circ z}{K_{sen}}\right)$, where z is a non-negative integer.

Note that (2.16) is only one of many possible choices for $\phi_{k_{ring}}$ and results in the proposed spiral arm array shown in Fig. 2.12. Other choices will result in different variants of spiral arm array geometries.

2.6 Conclusions

In conclusion, before a beamformer can be designed, it is necessary to understand the target application of the beamformer as well as the environment that it will be operating in. This is because most of the designs of beamformers are formulated upon a certain acoustic environment model, including types of signal source, propagation medium and sensor array. Proper study and modelling of these environmental factors are necessary to ensure designed beamformers to work. It is also essential to capture and model these factors as close as possible to its practical counterparts so that the designed beamformers, verified theoretically or through simulations, will continue to work when deployed to its real-world application environment.

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