11. The sound field and how it is measured

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Contents:

Introduction.

This lecture addresses the sound field, which according to the encyclopaedic definition is the region of space where there is sound. The topic of the lecture, then, will be to address the spatial properties of sound and of sound emitters and receivers. I will also try to address practical considerations of experimental design and sound field measurement.

After a more strict definition, the sound field would be the pressure gradient, i.e. the space derivative of sound pressure. The sound field so defined would be an analogue to the electrical field (the potential gradient or force acting on a unit charge). A very important aspect is that the sound field is both a property of the source and of the surroundings. Also, all information about the sound is contained in the pressure gradient, and for example sound direction or of sound intensity calculations depend on estimation of the pressure gradient.
However, the term 'sound field' is almost always used in a colloquial sense as:

1. **Near field** (1), the region near the sound emitter where medium motion is dominated by local hydrodynamic flow – also called the hydrodynamic near field
2. **Near field** (2), the region near the sound emitter where sound radiation is complex due to interferences between sound radiated from different regions – also called the geometric near field or the Fresnel zone. I will not discuss these effects here, since they have been covered in Magnus' lecture.
3. **Far field**, the region far from the sound emitter where medium motion is dominated by the propagating sound wave
4. **Free sound field**, i.e. a region without reflected components far away from emitter
5. **Diffuse sound field**, a region with reflected component and zero net radiated sound energy
6. The term **'closed-field sound'** is used for sound in small enclosures (earphone couplers) that are essentially pressure chambers.

Properties of the sound field – sound pressure, particle motion and intensity.

A sound wave is a longitudinal wave that propagates in an elastic medium with a propagation speed that only reflects the physical properties of the medium. The sound wave is usually characterised by its pressure and motion parameters.
The sound wave generates alternating condensations and rarefactions of the medium particles, i.e. an alternating pressure. Also,the particles are displaced and oscillate in the propagation direction around their rest position (the particles make no net movements although the sound wave propagates) (note that an acoustic particle is a 'tiny bulk' of medium, so small that it can be regarded as a unit and so big that it retains fluid properties, i.e. containing a large number of fluid molecules).
Three related parameters describe the one-dimensional motion of the acoustic particles:

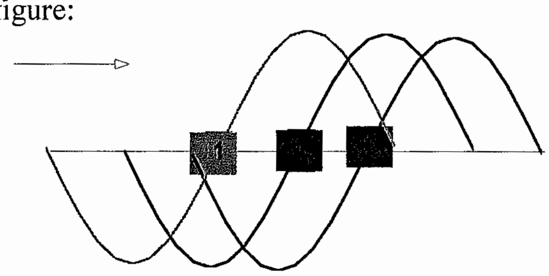
Displacement, $\vec{x}(t)$

Velocity $\vec{v}(t) = \frac{\partial \vec{x}}{\partial t}$

Acceleration $\vec{a}(t) = \frac{\partial \vec{v}}{\partial t} = \frac{\partial^2 \vec{x}}{\partial t^2}$

(Please do not confuse particle velocity with sound velocity. Particle velocity is proportional to the source level, whereas sound velocity is a constant only depending on properties of the medium.)
The medium motion parameters are vectors parallel to the propagation direction of the sound wave and thus directional; Sound pressure, in contrast, is non-directional. However, the pressure gradient is directional and proportional to particle velocity (see below). Note that the motion parameters are ambiguous- the particles oscillate both parallel and antiparallel to the sound propagation direction.

In the propagating sound wave, sound pressure and particle velocity are in phase. This is a fundamentally important fact of sound. You may appreciate this fact intuitively from the following figure:



The figure shows the displacement experienced by each of the acoustic particles as the sound propagates (direction shown by left arrow). Note that the displacement is oriented along the direction of propagation; the sine waves only shows the magnitude of displacement. Particle 1 leads and when particle 2 has its peak velocity at rest position (particle velocity is the derivative of displacement, therefore maximal velocity corresponds to zero displacement, i.e the rest position) the two other particles move against it (having opposite-sign displacements), creating a peak pressure. Therefore, the particle velocity is in phase with the pressure in the propagating sound wave.

Sound intensity.

Sound intensity is the energy radiated through a unit area by the propagating sound wave. The sound intensity is calculated from the particle velocity as the time average of pressure and particle velocity.

$$I_r = \overline{p \cdot \vec{v}_r}$$

Note that velocity components 90 deg out of phase with pressure cancel (the time average is zero). These components belong to the reactive, non-propagating sound field. Examples are standing waves and local hydrodynamic flow, but also in diffuse sound fields (i.e. sound in small, hard enclosures) the intensity vector will vanish.
Generally, the two parameters – sound pressure and particle velocity – must be measured independently, but far away from the sound source (where local hydrodynamic flow is negligible) sound pressure and particle velocity are related by Ohms acoustical law

$$p = v \cdot Z, Z = \rho \cdot c$$

where Z is the characteristic impedance of the medium, ρ the density and c the speed of sound. The relationship between pressure and velocity is called Ohms law, because it is directly analogous to the relationship between electrical potential and current. When people refer to far-field sound they mean sound at distances where Ohms acoustical law holds. Here sound intensity (energy flow per unit area) can be calculated as:

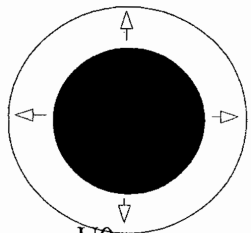
$$I = p \cdot v = \frac{p^2}{\rho \cdot c}$$

which is the normal equation we use in everyday calculations on the assumption that we are dealing with far-field sound.

Generation of the sound field (Sound emitters).

1. The acoustic monopole.

To understand the limits of the far field, it is instructive to look at some simple sound emitters. The simplest is the acoustic monopole – a pulsating sphere. It may look like a very idealized object, but all sound emitters can be constructed from an assembly of monopoles. Furthermore, the emission of many sound-producing animals can be approximated by single acoustic monopoles.



The monopole generates two kinds of disturbances in the medium:
Propagating sound wave radiating out from sphere
Local flow- medium displaced radially by pulsations of sphere

In the monopole, local flow vectors are aligned with sound propagation direction
The two terms mentioned above show up in the equation for radial particle velocity (r distance, U0 source velocity, k wave number)

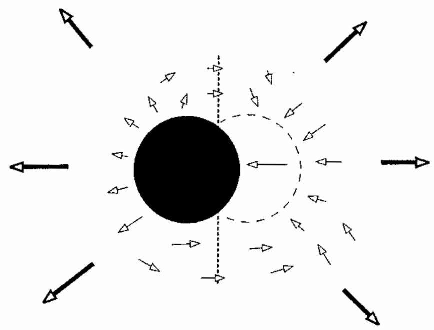
$$v = -\frac{ka^2}{r} U_0 \sin(\omega t - kr)) \qquad \textit{(sound-wave term)}$$

$$+ \frac{a^2}{r^2} U_0 \cos(\omega t - kr) \qquad \textit{(local flow term)}$$

Pressure is given by the equation: $$p = -\frac{\rho cka^2}{r} U_0 \sin(\omega t - kr)$$

Thus, the sound wave pressure and velocity again are in phase, resulting in a propagating sound wave and a non-zero intensity. However, pressure and local flow velocity are 90 deg. out of phase, and the local flow therefore does not contribute to the sound intensity. Note that the local flow term is local because it decreases with the square of the distance (i.e. 12 dB/DD as opposed to the 6 dB/DD of far-field sound). Note the ka and kr term, showing the importance of distance and size of the emitter.

2. The acoustic dipole(translating sphere)
The acoustic dipole is equivalent to two monopoles 180 deg out of phase.Therefore, at equal distances from the centers of the monopoles, sound pressures cancel (stippled line), i.e. sound radiates in a 'figure-eight'-pattern (red arrows).
The local flow field is shown by arrows. If the wavelength is large compared to the sphere , sound emission is 'short-circuited' by local flow (so sound emission will be small). Note that, unlike the monopole the dipole local flow field is not aligned with the sound field.



3. The acoustic quadrupole
A quadrupole is two dipoles (i.e. four monopoles) oscillating with alternate phases. The sound emission is maximal in the direction of dipole movement, and again the sound emission is cancelled in regions equidistant to the two dipoles (i.e., 45 deg from the dipole axes), so sound will radiate in a 'flower-shape' pattern. Again, the local flow field is not aligned with the sound field.

The local flow – a near field?

Traditionally, the local flow has been called a near-field effect. Near/far fields are not very precise terms, however, (for one thing, 'near field' is used for two different effects) and the term should be avoided for the following reasons:

1) Animals have receptors for medium motion or sound pressure. Hence, any motion or sound pressure whether originating from local flow or sound wave can stimulate the relevant receptors - i.e. there are no specialized near-field/far field receptors.

2) The rules of thumb for 'extension' of the near field (e.g. 1/6th wavelength) only hold for monopole sound emitters. For dipoles and quadrupoles, in the directions where sound emission is minimal local flow can dominate at greater distances.

Instead, it is recommended to distinguish between the local hydrodynamic flow and the propagating sound wave. It is also recommended to measure the medium motion when working within a wavelength of the sound emitter, if the animal respond to the motion components of sound.

Practical bioacoustical considerations.

How do these considerations apply to bioacoustics? Well, two questions may be asked. One is how animals measure these parameters, another is how we would measure them and design our setups

Biological devices (ears).
Animal ears measure or estimate sound field parameters to estimate the location of the sound source. This is typically done by measuring sound pressure or estimating the pressure gradient.Sound pressure is non-directional, and typical pressure receivers are closed with sound access from one side only (but these receivers like any other sensing membrane actually respond to the pressure difference across the membrane). However, the neural comparison of inputs from two pressure receivers can give information on the propagation direction of the sound wave through the measured differences in arrival time at the two ears or through the sound shadowing of around the body and head of the animal. The situation in fish is different, since they apparently have one pressure receiver. The current hypothesis is that the CNS of fish combine the input from the pressure receiver (swim bladder coupled to the inner ear) with measurement of direct particle motion by one of the inertial otolithic organs.
Alternatively, since the medium motion is directional, receivers that respond to medium motion will show some directional sensitivity. Such receivers will show 180 deg. ambiguity, but note that combining a measure of medium motion with pressure can resolve this ambiguity, in far-field sound, at least, since the true direction is where sound and velocity is in phase. The simplest receivers are the diverse types of sensory hairs with some kind of intrinsic directionality (like the hair cells in vertebrate lateral lines and inner ear). Such sensory hairs usually have an excitatory response in a certain direction and an inhibitory response in the opposite direction. Outside this axis, the response decreases, leading to a figure-of-eight characteristic.
The third type of receivers is the pressure-difference (or –gradient) receivers. Here sound can enter both sides of a membrane producing cancellation when sound pressures at the two sides have identical amplitudes and phases, comparable to the principle of a directional microphone. These receivers are only directional in a limited frequency range and their directional characteristics may change with frequency.

2) How is it done technically?
Sound pressure is measured with microphones that respond to the pressure gradient across a membrane and in water by hydrophones that contain piezoelectric transducers for pressure. Pressure gradient microphones can be constructed to allow sound to enter both sides om membrane, and such microphones will be directional.

Generally, pressure and particle velocity are two independent aspects of the sound field and must be measured independently. In principle, devices that measure air flow could also respond to particle velocity – if they are fast enough. This rules out devices such as hot-wire anemometers. Currently, there are three main approaches to measure particle velocity.

1. Particle velocity can be measured directly by a transducer that is translated by the water particles and emits a signal proportional to the translations. The transducer needs to have the same density as the surrounding medium. This rules out direct measurements in air, but in water it is possible to design a transducer (a small solenoid) with the same density as water.

2. Indirect method – estimation of the pressure gradient.
   From Newtons 2. Law,

$$\rho \cdot \frac{\partial v_r}{\partial t} = -\frac{\partial p}{\partial r}$$

$$\Downarrow v_r = -\frac{1}{\rho} \int \frac{\partial p}{\partial r} \cdot dt$$

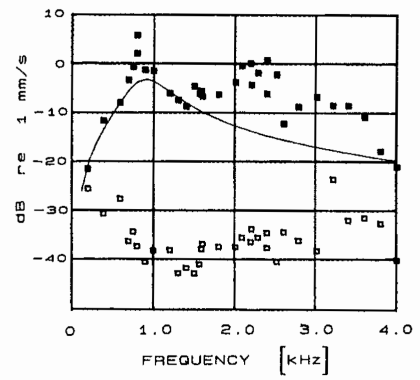
it can be seen that particle velocity is proportional to the pressure gradient. Particle velocity is inversely proportional to the medium density ρ and will therefore be much smaller in water than in air (by a factor 3570 for identical sound pressures).

In practice, the pressure gradient can be estimated by measuring the pressure difference on two closely spaced (spacing Δr) hydrophones or microphones, integrating and scaling, i.e.

$$v_r(t) \approx \frac{1}{\rho} \int \frac{(p_1(t) - p_2(t))}{\Delta r} dt$$

Note that this is the velocity component on the axis of the two transducers. There are two additional orthogonal components of particle velocity that can be measured by turning the two transducers. The transducers must be completely equal in amplitude and phase response, since any difference will produce spurious velocity components.

Particle velocity measurements are routinely made in air using a two-microphone technique (Fahy 1996), but have not been used much in underwater measurements, probably because of the very small velocities.



The figure shows laser measurements of clawed frog tympanic disk vibrations (filled squares) and particle velocities (open squares) in response to underwater sound. The particle velocities were measured using the pressure gradient method with two closely spaced hydrophones (Christensen-Dalsgaard et al. 1990). We used the particle velocity measurements to show that the eardrum responded to sound pressure.

3. Another indirect method is particle imaging velocimetry (PIV). The technique is based on the idea that it is possible to make two snapshots of fluid particles (in this case, tiny, opaque grains suspended in the fluid) by illuminating the fluid with brief laser pulses and from an algorithm assuming minimal movements of the particles to calculate the most likely displacement of them. The main problem with this method is that it is expensive and not very portable.

Once sound pressure and particle velocity have been measured the sound intensity can be calculated to give the active, radiating sound component emitted from the source.

Experimental manipulations of the sound field.

Local flow/sound considerations:
Because of the ka/kr dependence (the relative importance of the two components depend on wavelength and distance) these considerations are most important for low frequencies and underwater sound, where the wavelengths are long. Generally, there is no way to avoid local flow generation by a sound emitter. The best way to minimize the local flow is to move the setup away from the sound

emitter by at least a wavelength. In the literature, 1/6th of a wavelength is sometimes quoted as a rule of thumb. It is probably only safe for monopole emitters. If the question is important and you are in doubt, measure (i.e. measure the particle velocity and check whether the pressure/velocity conform to Ohms law).
If you are interested in studying particle motion sensitivity minimize sound emission of the stimulator (by minimizing ka - use small vibrating spheres or air puffs; alternatively vibrate the whole animal) and calibrate the motion component directly.
Loudspeakers vary tremendously in the sound field they generate. It is up to the experimenter to select/build omnidirectional speakers or very directional ones depending on the question asked.
The low-frequency radiation of speakers can be improved dramatically by baffles; the directionality can be changed by different types of horns or by combining loudspeaker units.

Standing wave tubes.
In a standing wave, sound pressure and particle velocity are 90 deg out of phase, so distinct pressure and velocity nodes form in a standing wave tube. Such devices have traditionally been used to investigate whether ears responded to the pressure or velocity component of sound

Diffuse/free sound fields
For investigations of directional hearing it is desirable to avoid reflected components in the sound field, i.e. to work in a free sound field. The most obvious solution in air is an anechoic room with structures that absorb reflections. However, anechoic rooms are nearly always too small (making it difficult to avoid reflections at low frequencies). Note that audiometric cabins (such as the IAC) are sound- proof, but not really anechoic, at least not below 1000 Hz. Reflections can be removed digitally if the reflections do not overlap the investigated structures' impulse response. This is generally not possible in water (there is usually major reflections from surface and bottom). In air, however, short transients (click) can be used to excite the structure and a time window chosen that just contains the impulse response and eliminates the echoes.
In water, it is generally very difficult to get a free sound field, because the wavelengths are large and it is very difficult to make a non-reflecting tank. Consequently, the cleanest experiments in fish directional hearing have been undertaken in deep Norwegian fiords or Scottish lakes. However, most of the fish auditory specialists (ostariophysi) live in shallow water, so it obviously has merits to understand the acoustics of their habitat. Shallow water (depth comparable to wavelength) should be considered as a special medium (Kuperman and Lynch 2004) with different properties than deep oceanic water (for one thing, the shallow water medium acts as a high-pass filter with a cut-off-frequency that depends on water depth and bottom material).

For some investigations, it can be useful to have a diffuse sound field where there is essentially no propagation of sound. The ultimate diffuse sound field is a pressure chamber such as a closed coupler or a small water tank. If the enclosure is sufficiently small compared to the wavelength it can be assumed (or better measured) that sound pressures are equal everywhere in the enclosure. However, at smaller wavelengths, standing waves can be formed, creating pressure and velocity nodes.

If there is one take-home message of this lecture it is that it is important to calibrate and measure. Most importantly, however, the behavior and sensitivity of the animal in question defines which measurements are relevant. If you are interested in studying low-frequency underwater sound (fish hearing) in the laboratory, you have to attend to the intricacies of hydrodynamic flows and probably be able to measure particle motion components.

Suggested reading:

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