Fundamentals of wave propagation

The most important qualitative statements about wave propagation can be deduced by everyday life experience. When observing temporary, frequently repetitive sound incidences, such as a child bouncing a ball, hammering at a construction site, etc., a time delay can easily be observed between the optical perception and the arrival of the acoustic signal. This time delay increases with increasing distance between the observer and the source. Apart from the facts that

- the sound pressure level decreases with increasing distance and
- sound sources have a radiation pattern and
- echoes accumulate, for instance, at large reflecting surfaces (like house walls) or, more generally, if the ‘acoustic environment’ (ground, trees, bushes, etc.) is left out of our considerations,

the only thing that distinguishes different observation points is the time delay. Indeed, sound incidences sound the same from any vantage point, as the frequency components are the same. The wave form of a sound field (in a gas) is not altered during propagation. The propagation is called ‘non-dispersive’, because the form of the signal is not altered during wave transmission. In contrast, the propagation of bending waves in beams and plates, for instance, is dispersive in gases (see Chap. 4). The fact that sound fields do not alter their wave form during transportation is not trivial. Non-dispersive wave propagation in air is not only an essential physical property of sound travel; imagine if sound incidences were composed differently at various distances. Such a case would render communication impossible!

This chapter attempts to describe and to explain the physical properties of wave propagation in gases. First, it seems reasonable to clarify the physical quantities and their basic relations, which are needed to describe sound fields. This chapter should likewise serve as a means to refresh basic knowledge in thermodynamics. The following deliberations are based on the assumption of perfect gases. This assumption in respect to air-borne sound in the audible
frequency range is justified by extensive experimental evidence with highly significant correlation.

2.1 Thermodynamics of sound fields in gases

The physical condition of a perfect gas, starting with a given, constant mass $M$, can be described by

- its volume $V_{t_0}$ it fills
- its density $\rho_{t_0}$
- its inner pressure $p_{t_0}$ and
- its temperature $T_{t_0}$.

When conducting theoretical experiments with a small and constant mass of a gas, bound, for example, by a small enclosure with uniform constant pressure and uniform constant density, the state descriptions of volume, temperature, and pressure are the most illuminating. The density $\rho_{t_0} = M/V_{t_0}$ then appears as a redundant quantity which can be determined by the volume. It is enough to describe the gaseous state of large (sometimes infinite) masses and volumes—relevant when dealing with sound fields—in terms of pressure, density and temperature, but for the purposes of review in the basics of thermodynamics, the following theoretical investigations outlined below will focus on constant gas masses. Sometimes, however, the following derivations are based on , since the origins of thermodynamics should be refreshed as mentioned earlier. The principles from the following discussions will then be appropriately applied to the important sound field quantities.

As a matter of fact, the question arises as to how the quantities used for describing a gaseous state are related. The criteria of a constant mass of a gas (when put, for example, into a vessel with a variable volume) should be met and can be approximately described as such:

- heating of the gas with constant volume results in an increased pressure $p_{t_0} \sim T_{t_0}$
- the pressure of the gas is inversely proportional to the volume $p_{t_0} \sim 1/V_{t_0}$.

These and other such statements can be summarized in the Boyle-Mariotte equation, if one accounts for the fact that an increased mass (with constant pressure and constant temperature) needs an increased volume. It is given by

$$p_{t_0}V_{t_0} = \frac{M}{M_{\text{mol}}}RT_{t_0}, \quad (2.1)$$

where $M_{\text{mol}}$ is a material constant, the so-called ‘molar mass’. The molar mass $M_{\text{mol}}$ defines the ‘molecular mass in grams’ of the corresponding element (see the periodic system of elements), e.g. $M_{\text{mol}}(N_2) = 28$ g and $M_{\text{mol}}(O_2) = 32$ g which results in $M_{\text{mol}}(\text{air}) = 28.8$ g (air consists of approximately 20% oxygen