The final group of noise control problems which we will briefly discuss here concerns the control of sound propagation in ducts. Ducts can be viewed as enclosures where one dimension is very long, often terminating into open space. Common examples of a duct include the airways used in central heating and cooling systems, and any piping system (including vehicle exhaust systems). Another example of a duct which may not be so obvious is a long hallway connecting two adjacent rooms or halls. The essential acoustic ingredient for a duct is that sound waves be constrained in two dimensions while being allowed to travel more-or-less freely in the third. For this reason, ducts are often referred to in acoustics literature as waveguides, where the constraining walls guide the travel of sound waves in the third dimension.

Once again, before we examine passive and active noise control approaches to attenuating sound propagation in ducts, we will examine important characteristics of the sound field in ducts. Once a set of characteristics is established it is straightforward to understand and optimize the physical mechanisms behind the noise control approaches.

Sound Fields in Ducts

The idea that a duct is simply an enclosed space with the boundary removed on one side provides us with clues about the structure of a sound field in a duct. It is intuitive that in describing the sound field we should essentially be considering the bounded sides and the open sides separately.

The bounded sides can be expected to have a modal response, similar to that of a fully enclosed space. When a sound wave fits in the cross section the response will peak. The frequency where this occurs is a resonance frequency. If, for example, the duct cross section is rectangular, then we will have resonances for what are essentially axial and tangential enclosure modes.

The open side can be expected to have a response similar to that associated with free space sound radiation. In the absence of any boundaries, the
sound waves will simply travel away and there will be no resonance response associated with this side of the duct.

This intuitive model of sound fields in ducts is essentially correct. There are, however, some details which must be added to provide a complete description.

**Modes in Ducts**

Ducts *do* have a modal form of response. However, unlike modes in an enclosed space, duct modes are restricted to being one- or two-dimensional (associated with the cross section). Duct modes also propagate, or move down the duct.

The fundamental, or lowest frequency, mode in a duct is the *plane wave mode*. Referring to Figure 6.1, a plane wave has a uniform sound pressure distribution in the duct cross section, and has the same waveform of pressure distribution down the duct as an acoustic wave in free space. A plane wave does not have a “true” resonance response associated with cross section. In theory, the plane wave mode has a resonance frequency of 0 Hz, being an axial mode with an infinite length in one direction.

All modes in the duct other than the plane wave mode are referred to as *higher-order modes*. These modes have an enclosure-like modal pressure distribution in the cross section.

It was mentioned that duct modes will travel, or propagate, down a duct. We can view the acoustic energy that is flowing down a duct to be divided up amongst the traveling modes; each mode carries a bit of the total energy. One of the most important results in duct acoustics is that a duct mode can only travel if the frequency of sound is greater than or equal to what we have been thinking of as the resonance frequency of the mode. Because of this result, ducts modes are usually referred to as having a *cut-on* frequency, rather than a resonance frequency. At all frequencies above this one, the duct will be “cut-on” and physically allowed to carry acoustic energy down

![Figure 6.1. Plane wave sound propagation in a duct. Note that the pressure distribution is uniform in all duct cross sections, and that the pressure peaks and troughs travel down the duct at the speed of sound.](image-url)