A GENERAL INTRODUCTION TO AEROACOUSTICS AND ATMOSPHERIC SOUND

James Lighthill

Department of Mathematics
University College London
Gower Street, London WCIE 6BT
UNITED KINGDOM

1. Broad Overview

This general introductory paper is devoted to Interactions of Sound with Air, including transmission through the atmosphere and both generation of sound by and propagation of sound in airflows

(e.g., manmade flows - around aircraft or air machinery - or natural winds) as affected by the air's boundaries and atmospheric composition; with (conversely) generation of airflows by sound (acoustic streaming).

From linear acoustics I utilize the properties of the wave equation, including

(i) the short-wavelength ray-acoustics approximation (Lighthill, 1978b, hereinafter denoted WF, pp. 67-) and

(ii) the theory of multipole sources (WF, pp. 31-) - with the long-wavelength "compact-source" approximation (source region of size \( \ell \) with \( \omega \ell/c \) small, where \( \omega \) = radian frequency, radiates like a concentrated source);

while from nonlinear acoustics I use (WF, pp. 150-) the physics of waveform shearing and shock formation.

Techniques special to aeroacoustics and atmospheric sound are centered on the momentum equation for air. Its difference from a wave-equation approximation include

A. Linear effects, of gravity acting on air stratified as meteorologists observe; effects which allow independent propagation (WF, pp. 292-) of "internal" gravity waves and of sound, except at wavelengths of many kilometers when the atmosphere
becomes a waveguide (WF, pp. 425-) for global propagation of interactive acoustic-gravity waves;

and (still more importantly) include

B. Nonlinear effects, of the momentum flux $\rho u_i u_j$; i.e. the flux – rate of transport across unit area – of any $\rho u_i$ momentum component by any $u_j$ velocity component. This term, neglected in linear acoustics, acts like a stress (i.e. force per unit area – since rate of change of momentum is force). In particular,

(i) an airflow’s momentum flux $\rho u_i u_j$ generates sound like a distribution of (time-varying) imposed stresses; thus not only do forces between the airflow and its boundary radiate sound as distributed dipoles, ($\rightarrow F \simeq - + F$) but also such stresses (acting on fluid elements with equal and opposite dipole-like forces) radiate (WF, pp. 63-) as distributed quadrupoles; ($\leftrightarrow \simeq - + + -$) (Lighthill, 1952 and Lighthill, 1962)

(ii) the mean momentum flux $\langle \rho u_i u_j \rangle$ in any sound waves propagating through a sheared flow (with shear $\partial V_i / \partial x_j$) is a stress on that flow (Lighthill, 1972 and WF, pp. 329-), and the consequent energy exchange (from sound to flow when positive, vice versa when negative) is

$$\langle \rho u_i u_j \rangle \partial V_i / \partial x_j;$$

(iii) even without any pre-existing flow, energy-flux attenuation in a sound wave allows streaming to be generated (WF, pp. 337-) by unbalanced stresses due to a corresponding attenuation in acoustic momentum flux – essentially, then, as acoustic energy flux is dissipated into heat, any associated acoustic momentum flux is transformed into a mean motion (Lighthill, 1978a and WF).

And another (less crucial) momentum-equation/wave-equation difference is

C. Nonlinear deviation of pressure excess $p - p_0$ from a constant multiple, $c_0^2 (p - p_0)$, of density excess.