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A REVIEW OF SOUND PROPAGATION IN THE LOWER ATMOSPHERE

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An understanding of phenomena affecting the propagation of sound in the real atmosphere is necessary for the correct interpretation of many field data and for the prediction of noise from aircraft or from road traffic. Another recent application has been in estimating the range of sirens used as audible warning devices. The aim here is to review briefly the factors affecting sound propagation in the lowest few hundred metres of the atmosphere.

1. Refraction

Sound refraction takes place whenever sound rays encounter a non-zero velocity gradient which is not parallel to the direction of propagation. In the atmosphere such a velocity gradient is principally brought about by non-uniformity of wind speed and of temperature and can give rise to the formation of shadow zones. The main variation in mean wind and temperature occurs in a direction normal to the surface and, to first approximation, the atmosphere can be considered as a horizontally-stratified medium. Typically wind-velocity increases with height but the temperature gradient may be either negative or positive. If it is assumed that the gradient of the velocity of sound is constant with respect to height, then simple application of Snell's law permits the ray-path of the sound waves to be derived. The distance from an elevated source at which the shadow-zone is formed can then be easily predicted.

Although this simple approach is useful in illustrating certain features associated with the sound field around an elevated source in a layered atmosphere, it cannot yield quantitative data for practical situations. It is well known that temperature and wind profiles in a real atmosphere differ considerably from simple linear functions of altitude. Empirical attempts have been made to overcome this problem but agreement between experimental and calculated values of the shadow range is poor. It is therefore necessary to use more realistic temperature and wind profiles.

The wind gradient at lower levels measured over a large uniform surface is determined mainly by surface roughness, temperature gradient, and the wind speed at a reference height. Over open smooth ground and grassland, and under conditions of neutral stability, a logarithmic law for the variation of mean wind speed with height has been shown to be valid. For structural design purposes under open farmland conditions a power-law velocity profile for high-wind conditions has also been used and for prediction purposes data on the frequency of occurrence of given wind speeds for different parts of the country are available.

Temperature gradients in the air layers near the ground are complex, showing strong diurnal variation caused by solar radiation; there is a distinct tendency for temperature lapse to occur during the day and for temperature inversion to occur during the night. In a moderate wind neutral stability or temperature lapse is most likely and this represents the condition most disadvantageous for upwind sound propagation; the mean temperature varies approximately logarithmically with height above ground but such a relation holds only up to heights of ten or twenty metres at most in summer and even less in winter. Above this height the thermal effects of the ground become unimportant and the mean temperature gradient typically approximates the moist adiabatic lapse rate.

It must be emphasized that appreciable variation about such wind and temperature profiles is to be expected, but the above relations provide useful design criteria.

Geometric ray theory is valid only if the relative change in amplitude, the change in direction cosines and the relative change in sound velocity per wavelength are much less than unity. In normal near-ground propagation all frequencies above about 400 Hz are refracted equally, but at frequencies below this refraction tends to decrease. Some idea of the effect of any given wind and temperature profile for a given frequency can be obtained if, instead of using actual gradient values at each point along the ray path, the mean value averaged over one wavelength in a vertical direction is used. Snell's law of refraction at a layer then permits ray-tracing using numerical techniques (procedures commonly used in underwater ray-tracing problems). The resulting ray-paths are quite different from those derived from the simpler constant-gradient analysis and correlation between calculated and measured values of the range to the shadow boundary is good. For a source height of 10 m and a receiver height of 1.2 m the shadow range is typically between 100 and 200 m.

In the region between the source and the sound shadow the sound intensity is little affected by refraction. At the shadow boundary the transition zone extends over a considerable distance and even at points far into the shadow zone the attenuation in excess of spherical spreading rarely exceeds 25-30 dB.

2. Terrain

For an elevated source over flat grassland an attenuation considerably in excess of that predicted from simple spherical spreading is observed due to absorption of sound at the air/ground interface, and this attenuation is highly frequency dependent. Field measurements have generally included effects of ground absorption and shadow formation; rarely have sufficient meteorological data been recorded to permit the two effects to be unequivocally resolved. However, from a series of investigations of near-ground propagation carried out by the Building Research Station, a reasonable quantity of downwind data (where shadow-formation effects are minimal) is available which permit estimates to be made of the effects of ground absorption. Recently the author has shown that such effects can be explained theoretically; when source/receiver separation is large the asymptotic solution for the field due to a source above a finitely absorbing plane can be interpreted simply in terms of an image source with a relative strength in any direction given by the complex plane-wave pressure-reflection coefficient for that direction. In the unfortunate absence of reliable data on the acoustical properties of grass-covered soil for the relevant frequency range, normalized curves of characteristic impedance and propagation coefficient relating to fibrous absorbents have been used; results are in reasonable agreement with field data. The main value of such an analysis is in showing the change in excess attenuation with changes in the acoustical properties of the ground, the angle of incidence, and the height of the source and receiver above the ground.

With sound source and receiver both at considerable height above the ground, no ground-absorption effects will be observed; wind and temperature gradients (and thus sound-refraction effects) are also much reduced. This is confirmed by field measurements of propagation between neighbouring mountain tops where even over distances of 3km there was no evidence of any ground-absorption or refraction effects.

3. Air attenuation

Due to vibrational relaxation effects in oxygen molecules, absorption of sound in air is critically influenced by its water-vapour content and is highly frequency-dependent. Two important experimental studies of molecular absorption have been reported; by Evans and Bazley, and by Harris. It has been shown that each set of absorption data collapse to a single bell-shaped curve when the ordinate is normalized attenuation (ratio of measured attenuation coefficient at a given frequency and humidity to the maximum attenuation coefficient observed at that frequency) and the abscissa is normalized humidity (ratio, for given frequency, of the actual humidity to the humidity corresponding to maximum molecular attenuation). The two methods are also in good agreement as to the maximum value of absorption coefficient. However, as regards the variation of the humidity corresponding to maximum attenuation as a function of frequency, they agree only over a rather restricted range and this does lead to appreciable differences between the predicted values of attenuation. The maximum difference occurs at high frequencies for a relative humidity of about 45% and a temperature of 26°C but for many practical purposes the discrepancies are not important and average values can be adopted. Use of the normalized curves permits prediction of molecular absorption at frequencies above those used in the experiments referred to above and can be used with reasonable confidence up to about 25 kHz.

Attenuation due to classical viscous and thermal loss mechanisms increases as the square of frequency. Except at high audio frequencies and above, such attenuation is usually much less than that arising from molecular absorption and for most practical propagation problems can be neglected.

4. Fog and rain

For many years it was thought that the presence of fog produces greatly increased attenuation of sound but this is not, in fact, the case and a typical value for attenuation in a reasonably dense fog is only 1 dB/km. Indeed, the stable meteorological conditions usually associated with inland mist and fog (low wind speed and greatly reduced thermal gradients near the ground) are particularly favourable for enhanced range of sound propagation as shadow formation is either completely absent or the shadow range is much greater than usual. Even when accompanied by light rain, as in pre-frontal fogs, no noticeable additional attenuation has been detected, at least at low and middle audio frequencies.

5. Turbulence

A number of authors involved with studies of sound propagation from a spherically radiating source have reported that excess attenuation attributable to scattering by atmospheric turbulence is small, particularly for low and middle frequencies. Such a loss is expected to increase with frequency but there is little evidence of quantitative correlation between excess attenuation and degree of turbulence. However, the attenuation so caused is probably quite small - of order 1 dB/km. Scattering by turbulence may, however, have the effect of limiting the overall attenuation caused by ground absorption or shadow formation. Thus some places may intermittently experience a higher sound level than would be predicted by unqualified application of the corresponding attenuation data.

The structure of atmospheric turbulence and the resulting fluctuation in sound level has received detailed theoretical consideration. However, it is difficult to relate the quantities usually measured in field studies to theoretical results. Thus a commonly-observed quantity is the peak-to-peak fluctuation in sound level over a stated time interval but it is difficult to predict this because it depends critically on the higher moments of the statistical distribution of turbulence and on the response-time of the indicating instrument. On the other hand the coefficient of variation of the short-term mean-square pressure, although convenient theoretically, can only be determined from detailed digital analysis of recordings of signal amplitude as a function of time and, to date, no reports of field studies have included this information.

It is to be expected that the amplitude of fluctuations due to turbulence will generally increase with increasing distance from the source and with increasing frequency. Experimental data are available which permit rough estimates to be made of the amplitude of level fluctuations to be expected for typical near-ground sound propagation.

6. Shielding by obstructions

The effects on sound propagation of low obstructions on an otherwise plane ground are quite negligible in practice. Indeed, even barriers consisting of bands of mature trees have been found to have little effect on long-distance near-ground propagation. With large barriers, such as an extensive brick wall or row of houses, fairly well-defined shadow zones can be expected. With more complex urban environments it has proved possible to predict attenuation from an elevated sound source in terms of an 'urbanisation factor', whilst local effects due to shielding of traffic noise by different housing configurations have been empirically explained in terms of the percentage of the facade which is unobstructed.

A more detailed review by the author of the factors affecting near-ground propagation of sound is available as:
NPL Special Report 033, November 1969, "Range prediction for siren sources".