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Noise Testing of Vehicles— Acoustic Propagation Phenomena

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A RECURRING PROBLEM OVER THE LAST DECADE has been the variability of measurements using standard procedures for the noise testing of vehicles. What initially was believed to be a rather simple acoustic measurement has turned out in practice to include a surprising number of propagation phenomena, involving the state of the ground surface, the state of the atmosphere adjacent to this surface, and the interaction between the two. This paper represents an attempt to convey the author's current knowledge of these acoustic propagation phenomena to practicing engineers, hopefully in a form they will find useful.

Attenuation caused by the interference between direct and ground-reflected waves is considered first. This section is essentially an update of a review (1)* written six years ago, to which the reader is referred for a more detailed description of the basic phenomena. The next topic is atmospheric turbulence, where we consider the effect of atmospheric inhomogeneity along the propagation path of the noise on the variability of measurements. This inhomogeneity may be from naturally occurring atmospheric turbulence, or induced by the wake of the vehicle. Finally effects of refraction by the thermal boundary layer close to the ground are considered.

INTERFERENCE BETWEEN DIRECT AND GROUND-REFLECTED WAVES

Available theory relevant to ground interference effects (2) is developed in terms of the basic configuration shown in Fig. 1. A point source S and receiver R are situated above a plane earth. The direct sound travels along path r_1 to the receiver and the reflected sound along path r_2 which appears at the receiver to have come from the image source I. The interference between direct and reflected sound at R depends first of all on the reflective properties of the ground surface, which are usually expressed in terms of a complex acoustic impedance Z_2 of this surface relative to the characteristic impedance Z_1 of air. Both real and imaginary parts of Z_2 normally vary strongly with the frequency of the sound, and depend also on the grazing angle ψ.

The most detailed measurements of the impedance of a natural ground surface now available are for mown grass (3). A remarkably good fit to these measurements has been achieved by Chessell (4) using a simple model with a single adjustable parameter: the ground is assumed to reflect as if it were a semi-infinite porous medium, and the adjustable parameter is the flow resistivity σ - the resistance to flow of air in the pores per unit thickness of the ground (for which the only recognized unit is the rayl (CGS)).

To put present knowledge of ground interference into effective engineering practice a suitably simple technique is required, for measuring the ground impedance conveniently in any specific situation of interest. It would also be very useful to have measurements

*Numbers in parentheses designate References at end of paper.

ABSTRACT

A number of propagation phenomena which cause variability in the noise testing of vehicles using standard procedures have been isolated and studied. Included are the effects of interference produced by reflection from various ground surfaces, the effects of refraction caused by wind and temperature gradients in the atmosphere, changes in sound level due to the wake of the vehicle, and the effects of normal atmospheric turbulence.

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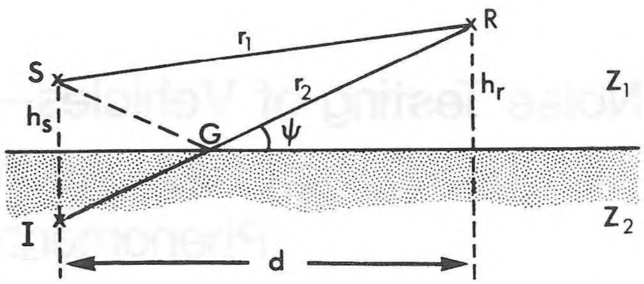

Fig. 1 - Reflection of sound from plane ground surface with impedance Z_2

obtained with this technique available for a variety of commonly encountered ground surfaces. With these goals in mind we have extended the analysis of Chessell to a variety of surfaces. It is accepted that the reflectivity of these surfaces may in time be better described by a more complex model, but the single parameter model is appropriate at present to both engineering needs and the present relatively primitive state of knowledge concerning the ground impedance.

POINT SOURCE - A single configuration was first chosen, that given by Fig. 1 with h_s = 0.3m (1 ft), h_r = 1.2m (4 ft), and d = 15.2m (50 ft). This choice was to maximize the relevance for noise testing using existing standard procedures, for example the noise from a snowmobile (5) or the exhaust noise from an automobile or light truck (6). The family of curves shown in Fig. 2 was then calculated for this configuration using the same equations as Chessell. This figure gives the predicted sound level at the receiver in the presence of the ground as a

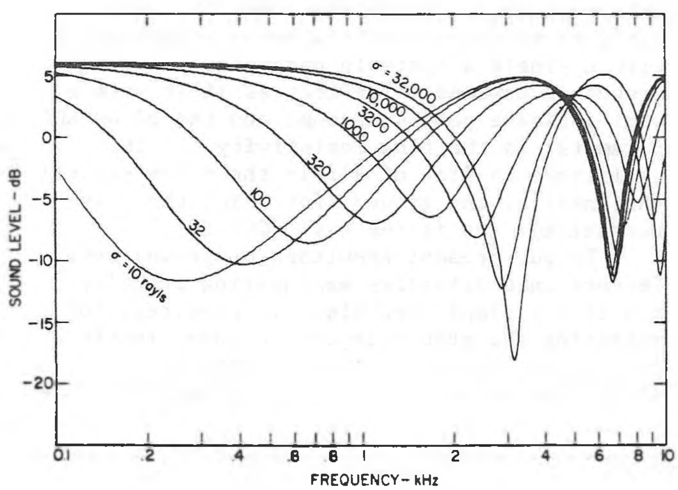

Fig. 2 - Predicted spectra for h_s = 0.3m, h_r = 1.2m and d = 15.2m in Fig. 1, and various values of the flow resistivity σ. The sound spectrum level is relative to that from the same point source at the same distance in free space

function of frequency for a range of values of the flow resistivity σ. The sound level is relative to that for the same point source at the same distance in free space.

Measurements were also made in the field of the sound produced in this configuration by an acoustic point source (1) using a pure tone and swept frequency. By arranging through a separate feedback loop that the acoustic power output of the source was independent of frequency, the measured frequency spectrum could be compared directly with the family of curves shown in Fig. 2 to obtain a value of the effective flow resistivity σ. The real and imaginary parts of the ground impedance were then obtained over a range of frequency from this value of σ using published graphs (4). The whole procedure, starting with setting up the apparatus on the site and ending with values of σ on the ground impedance, takes about half an hour (7). Values of σ for a number of sites obtained in this fashion are shown in Table I. Note the wide range in σ, extending from about 10 rayls for newly fallen snow to 20,000 rayls or greater for

Table I - Flow Resistivity for Various Ground Surfaces

Description of Surface	Flow Resistivity Giving Best Fit To Measured Spectrum: CGS Rayls
Dry snow, new fallen 7.5cm on a 40cm base	10 to 30
Sugar snow	25 to 50
In forest, pine or hemlock	20 to 80
Grass: rough pasture, airport, public buildings, etc.	150 to 300
Roadside dirt, ill-defined, small rocks up to 4"	300 to 800
Sandy silt, hard packed by vehicles	800 to 2500
"Clean" limestone chips, thick layer (1/2 to 1 inch mesh)	1500 to 4000
Old dirt roadway, fine stones (1/4" mesh) interstices filled	2000 to 4000
Earth, exposed and rain-packed	4000 to 8000
Quarry dust, fine, very hard-packed by vehicles	5000 to 20,000
Asphalt, sealed by dust and use	>20,000

old asphalt or concrete, and the variation in the excess attenuation shown in Fig. 2 that this range signifies.

APPLICATIONS - The relevance of the curves in Fig. 2 for vehicle testing may be understood by considering the spectrum of snowmobile noise in Fig. 3 measured using standard test procedures (5) over grass. It is well known that the maximum overall A-weighted level using these procedures is strongly site-dependent, and comparison of the spectrum in Fig. 3 with the inverse A-weighting curve shows the peaks due to the harmonics of the engine firing frequency to be significantly reduced in the region of 0.5 to 1 kHz due to the excess ground attenuation. Comparison of ground attenuation curves in Fig. 3 for σ = 150-300 rayls relevant for grass with those for 10-50 rayls relevant for snow indicates the differences one should expect for testing over these different surfaces.

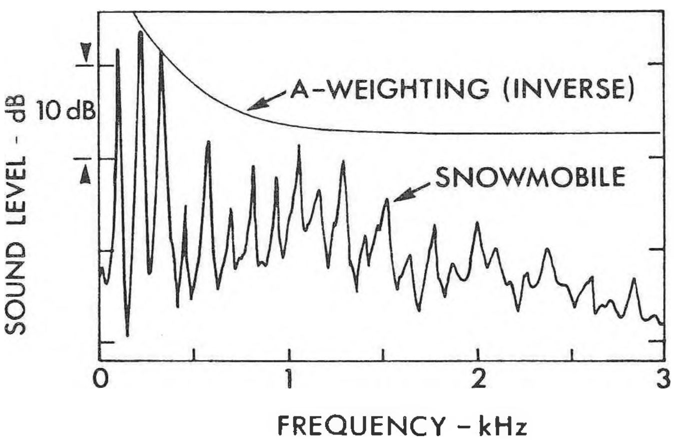

Fig. 3 - Measured snowmobile spectrum

One may note also that a test surface normally allowed for construction machinery is packed dirt. The ground attenuation indicated in Fig. 2 for σ in the range 800-2500 rayls found for hard-packed sandy silt (Table I) is by no means the same as that for a hard surface such as asphalt or concrete ($\sigma \gtrsim 30{,}000$).

It should be noted also, that it is not necessary to use the particular configuration h_s = 0.3m, h_r = 1.2m, and d = 15.2m either to determine σ via the procedure described above or to predict the excess attenuation due to the ground effect. A set of curves similar to those in Fig. 2 can be calculated using the same equations for any configuration.

LINE SOURCE - The positions of the sharp dips in the spectrum shown in Fig. 2 for hard surfaces ($\sigma \gtrsim$ 30,000 rayls) at 3 kHz and 9 kHz are strongly dependent on the measurement configuration, as they occur where the difference in path length between direct and reflected rays ($|r_2-r_1|$ in Fig. 1) are $\sim$1 and 3 half-wavelengths of sound respectively. For elevated noise sources such as truck exhaust stacks these dips occur down in the sensitive 0.1 to 1.0 kHz range of frequency where they provide a variability problem (1), while at larger distances they move up in frequency. It has been argued from time to time that the ground interference problem would be eased if an integrating sound-level meter were used for vehicle pass-by tests, as the interference filter shown in Fig. 2 should be greatly smoothed by the varying distance.

To test this hypothesis the sound level from an incoherent line source normal to the paper at point S in Fig. 1 has been calculated for otherwise the same configuration as that for Fig. 2 (h_s = 0.3m, h_r = 1.2m and d = 15.2m in Fig. 1). The results of these calculations are shown in Fig. 4. The reference level is again that for the same line source at the same distance in free space.

Comparing the curve in Fig. 4 for 20,000 rayls with that in Fig. 2, we find that the first dip in Fig. 4 is certainly much shallower than that in Fig. 2, but it has by no means disappeared by this smoothing process, and would probably still present a problem. The minima at lower frequencies for σ = 30 and 300 rayls are little changed in Fig. 4 from those for a point source in Fig. 2 because here the cancellation is due mainly to the change in phase on reflection rather than a difference in path length.

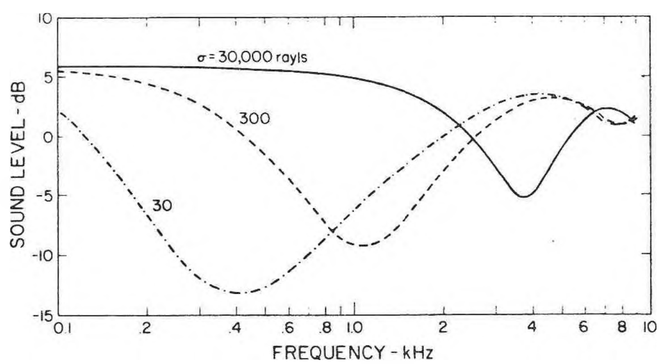

Fig. 4 - Predicted spectra for an incoherent line source and various values of the flow resistivity σ. The spectrum level is relative to that from the same source at the same distance in free space

It should be noted that the one parameter model used here, together with a relevant table of values for flow resistivity similar to Table I, if inserted into prediction schemes for environmental noise would represent a considerable advance over present procedures.

ATMOSPHERIC TURBULENCE

Large eddies are formed in the atmosphere by instabilities in the thermal and viscous boundary layers at the surface of the ground.

Further instability causes these eddies to break down progressively into smaller and smaller sizes until the energy is finally dissipated by viscosity in eddies approximately 1mm in size. A statistical distribution of eddies, which we call turbulence, is therefore present in the atmosphere at all times. The intensity of the turbulence is dependent on meteorological conditions, being high, for example, on a windy summer afternoon, and low under nocturnal inversions.

The inhomogeneity of the atmosphere in normal conditions of turbulence is much larger than is generally appreciated. Shown in Fig. 5 are typical daytime records of wind velocity and temperature. These measurements were taken simultaneously 1m above a large flat vehicle test area. Note for example that fluctuations in temperature of 5°C which last several seconds are common in the "steady" wind ($t<120$ sec in Fig. 5) and 10°C not uncommon. When the wind decreases to very low or zero velocity, slow drifts in temperature of the same magnitude are present, as for instance for $t \approx 180$ sec in Fig. 5.

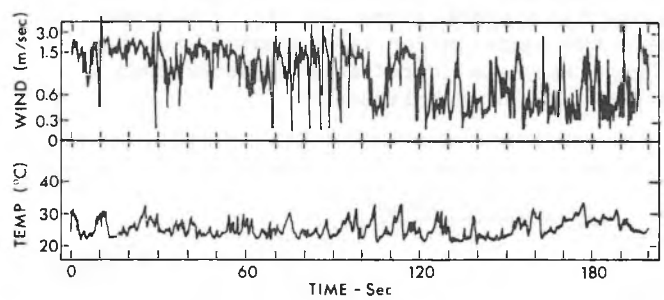

Fig. 5 - Typical daytime records of wind velocity and temperature. The measurements were taken simultaneously at a height of 1m over a large flat test area

The effect of normal atmospheric turbulence on wave propagation from a point source under conditions relevant to vehicle testing are now reasonably well established (8). Fluctuations of sound level (in decibels) of a pure tone should increase approximately as the square root of the frequency and linearly with distance.

AN EXPERIMENTAL INVESTIGATION - A series of experiments were conducted to find the influence of atmospheric turbulence in the propagation path, as well as other factors, on the variability of vehicle noise tests (9). The noise from an accelerating automobile was first measured (and tape-recorded) as specified by standard SAE J986a five times in succession (test 1). A multitone point source was then placed 0.3m above the ground at the point in the vehicle path closest to the microphone position. Without moving the microphone (or the source) 3 minutes of constant sound output from the multitone source was then tape-recorded. (The measurement configuration was here that shown in Fig. 1 with $h_s = 0.3$m, $h_r = 1.2$m and $d = 15.2$m.)

For the third test the multitone point source was attached to the automobile beside the exhaust outlet (which was the same height, 0.3m above the ground). The vehicle was run by the microphone in the same SAE J986a configuration used in the first test but at a constant speed of 48 kph (30 MPH). When near the microphone the engine was switched off and the multitone source switched on. Records of the sound from a calibrated point source simulating the exhaust noise from a moving vehicle were thereby obtained. This test was also repeated 5 times.

The sequence of three tests was conducted for one vehicle in about thirty minutes, and they were repeated for three vehicles. The whole sequence for three vehicles was also repeated for three different test sites and on twelve days selected for different weather conditions.

Run-to-run Variability - The characteristics of run-to-run variation were first investigated by frequency analysis (followed by statistical analysis) of the tape recordings for a given site and day. The standard deviation of the sound spectrum levels for two different days are shown in Fig. 6. The S's on the right give the variability of the amplitude of the pure tones received at the microphone from the stationary point source (test 2). Their characteristics are what is expected for propagation in normal atmospheric turbulence, as described above: the fluctuations in amplitude increase with increasing frequency and are larger for the day, when the sun is heating the ground, than for the evening.

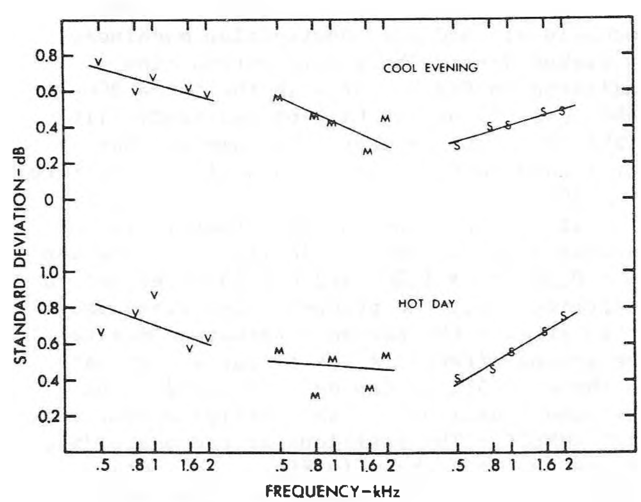

Fig. 6 - Standard deviations of sound level fluctuations for moving vehicles V, moving multitone source M and stationary multitone source S on a hot day and a cool evening - run-to-run variability

The M's in the center of Fig. 6 give the run-to-run variability in the maximum level of the pure tones from the moving point source (test 3) and the V's on the left the run-to-run variability in the maximum level of corresponding 1/3 octave bands of noise achieved by the accelerating vehicle (test 1). Comparing the characteristics of the M's, V's and S's, we find the behaviour of the M's and V's to be similar to each other, and different from that of the S's. The variability for both the accelerating vehicle and moving point source decrease (or at least don't increase) with increasing frequency, and also the difference between hot day and cool evening is not significant.

The similarity of M's and V's indicates that the performance of the vehicle or operator was not a factor in the V's, because the M's are for a calibrated source. The difference in behaviour between M's and S's indicates that both V's and M's are the result of motion of the vehicle (as the M's and S's are from the same point source). The likely mechanism, which fits the characteristics of the M's and V's in Fig. 6 is atmospheric turbulence caused directly by the wake of the vehicle. The greater variation at low frequencies is consistent with more large eddies than would be present in the stable statistical distribution of sizes described above. This is reasonable because the wake is the primary eddy, which exists before the stable distribution has time to form.

Day-to-day Variability (Effect of Weather) - The day-to-day variation of the A-weighted sound level was examined for a given site and type of test, and compared with the day-to-day variation in meteorological variables, namely temperature, temperature gradient, wind velocity and wind direction. The only significant correlation found was with the temperature.

The deviation of the sound level measured for accelerating vehicles using SAE J986a test procedures (test 1), when averaged for each site and day, from the mean for all days is shown in Fig. 7 plotted against the ambient temperature measured 1m above the ground. The dashed lines are fitted to the points for each site A, B or C individually, and the solid line gives the fit to all sites. The correlation with temperature, and the dependence on temperature given by the lines are comparable to what has been found elsewhere, and represent a considerable deterrent to regulation. The usual explanation of this temperature dependence is in terms of the density of the charge flowing through the engine and exhaust system.

However, we also examined the correlation of the day-to-day deviations for accelerating vehicles (test 1) shown in Fig. 7 with the equivalent for the moving point source (test 3) and those for the stationary source (test 2). The correlation of the test 3 results with those of test 1 was fairly high (62%), while

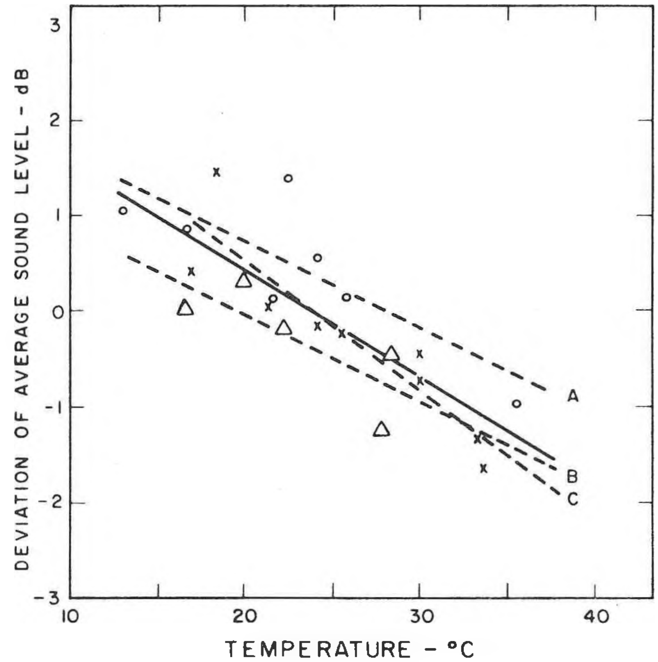

Fig. 7 - Deviations of average sound level attained for accelerating vehicles on different days from the mean for all days: O site A, Δ site B and X site C. The dashed lines are fitted to the points for each site, and the solid line to all points (day-to-day variability)

the correlation of the test 3 results with those of test 2 was low (24%) (10).

These measured correlations are incompatible with the day-to-day variation in measured sound levels for accelerating vehicles, as in Fig. 7, being in the noise source, as in the usual explanation given above. A substantial portion of it must lie in the motion of the vehicle, independent of the source, to provide the 62% correlation with the tests using an independent calibrated point source which moves with the vehicle, and the low correlation with the same source when stationary. Presumably this contribution is from the vehicle wake, as is the case with the run-to-run variability described previously.

REFRACTION

For acoustic propagation outdoors over distances longer than about 30m the effect of curved ray paths, or refraction, usually needs to be considered. The principal effects are illustrated in Fig. 8. For propagation downwind, or under temperature inversions (common at night) the refraction is downward, as shown at "a". The main effect here is usually to reduce the attenuation caused by ground interference. For propagation upwind, or under temperature lapse conditions, the sound refracts upwards as shown at "b" in Fig. 8. The main

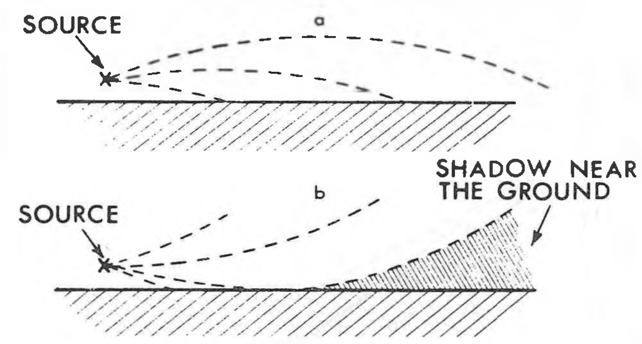

Fig. 8 - Forms of refraction, (a) for propagation downwind or during an inversion, and (b) for propagation upwind or during temperature lapse conditions

effect here is the creation of shadow zones, as indicated in the figure, where the sound level is commonly reduced by as much as 20 dB. In both cases, there exists a gradient of sound velocity in the atmosphere, and the refraction is towards the low velocity region.

For the noise testing of vehicles, significant propagation distances are normally kept to 15m or less in order to avoid these refraction effects, which would otherwise provide a strong dependence of measured sound level on the weather. However one needs a clear understanding of refraction phenomena to know when a measurement is at risk in unusual conditions.

THERMAL BOUNDARY LAYER - For significant refraction effects to occur in short distances, strong gradients of sound velocity are needed in the atmosphere, and one such gradient always exists close to the ground during sunny weather, caused by the heating of the ground surface by the sun.

Measurements of the vertical profile of temperature close to a paved test site on a sunny summer afternoon (9) where there is a relatively constant wind velocity of ∿6m/sec, and also on a calm cool evening for comparison, are shown in Fig. 9. The error bars give a rough indication of the variation in temperature. Note the existence of a thermal boundary layer during the daytime, which is confined in thickness to about 30cm by the wind, and that this layer virtually disappears in the evening. The narrow peaks on the temperature record for a height of 1m in Fig. 5, for example, are rising bubbles of hot air carried away by the wind, known as thermal plumes to the meteorologist.

The thickness of the boundary layer tends to increase with decreasing wind velocity, as the wind then becomes less effective at carrying away the hot air. The general increase in temperature shown in Fig. 5 for t≈180 sec indicates that the thickness of the boundary layer becomes larger than 1m during calm spells.

ACOUSTIC MIRAGE - It is a common experience

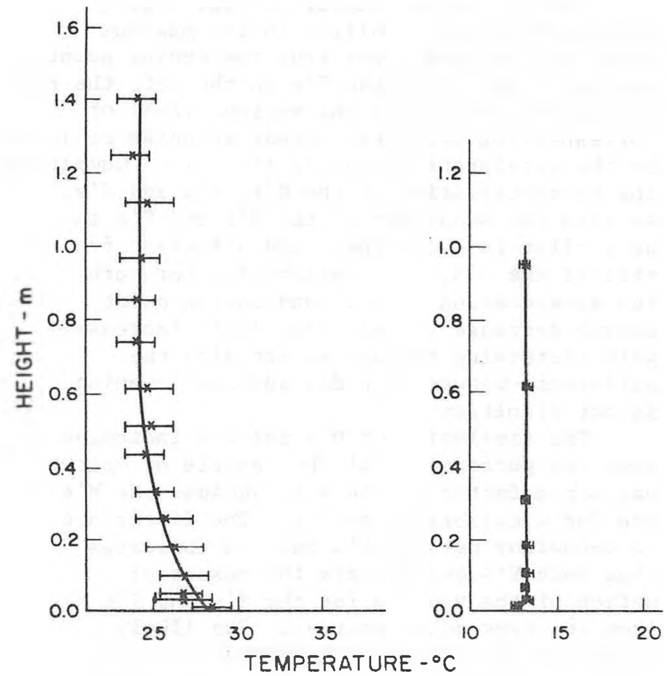

Fig. 9 - Measured vertical profiles of temperature over a large flat test site during a sunny and windy day on the left, and on a cool evening to the right

when driving an automobile to see what is apparently a pool of water on the road ahead, but in reality is a portion of the sky ahead, the light ray from which has been refracted upwards to the eye by the thermal boundary layer. This phenomenon is usually called a mirage. Since the velocity of sound is 1700 times more sensitive proportionally to the temperature than the velocity of light, powerful acoustic mirages (and shadow zones) must appear somewhere, due to the thin thermal boundary layer shown in Fig. 9, although this phenomenon does not seem to have been reported previously in the scientific literature.

To find whether such a mirage could influence measurements of vehicle noise, an acoustic point source emitting a pure tone was placed right on the surface on a flat asphalt site. Vertical profiles of both temperature and sound level were then measured on the site. The temperature profiles were similar to the daytime one shown in Fig. 9. The dashed lines in Fig. 10 show the measurements of sound level at a distance of 15m from the source and a height of 1.0m, for propagation both upwind and downwind, and the solid lines the same for a height of 0.5m. The sound level is relative to that for the same distance in free space.

Note that there is no significant excess attenuation of sound due to the thermal boundary layer at a height of 1.0m, but at 0.5m the excess attenuation becomes large, 10 dB or

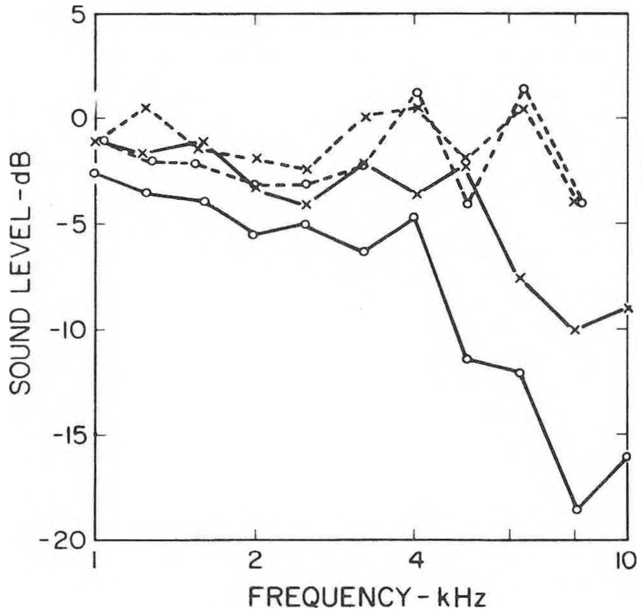

Fig. 10 - The acoustic mirage effect for propagation upwind (O) and downwind (X) for a microphone height of 1.0m --- and 0.5m ——. The spectrum level is relative to that from the same point source at the same distance in free space

greater, for frequencies greater than 4 kHz. There is at this distance from the source, therefore, a shadow boundary of the type shown in Fig. 8 at a height between 0.5m and 1.0m for frequencies higher than 4 kHz. The wind, whose velocity measured at a height of 1.3m averaged 1.0 to 1.2m/sec, was insufficient to destroy this shadow, although it did significantly affect the attenuation in the shadow zone (see Fig. 10). The shadow zone is present only at high frequencies, because the thickness of the boundary layer becomes small relative to the wavelength at low frequencies, hence ineffective as a wave refractor.

Measurements at a distance of 7.5m (not shown) indicated the shadow zone to be still present, but the shadow boundary to be lower than 0.5m. The measurements at ground level for this distance closely resembled those shown in Fig. 10 for a height of 0.5m.

Shadow zones may thus be present in acoustic measurements outdoors, at distances of 7.5 and 15m relevant to vehicle testing, in the presence of a thermal boundary layer similar to that shown in Fig. 9, due to this mirage effect. The significance of this shadowing for compliance testing of vehicles using procedures such as SAE J986a seems marginal. However the atmospheric conditions for the measurements shown in Fig. 10 should not be taken as an extreme. The dimensions of the boundary layer are obviously very volatile, and the shadow zones may be much enhanced for a hotter pavement or lower wind velocity, as an example. Thus care should be exercised in neglecting this effect for unusual conditions, particularly if a low microphone position is adopted.

The mirage effect shown in Fig. 10, however, throws considerable doubt on existing measurements of tire noise, where the noise source is presumably very close to the ground. The high frequency roll-off in spectrum level, characteristic of published measurements of tire noise, could be caused by refraction in the thermal boundary layer on the measurement site, rather than being characteristic of the tire. In practical situations where tire noise is important, for example in the propagation of noise from highways, this effect should also be taken into consideration.

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