The Influence of Atmospheric Turbulence on Barrier Sound Reduction

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Abstract

Numerical modelling and measurements are used for studying the reduced performance of a noise barrier, caused by a turbulent atmosphere. The turbulence scatters the sound, which leads to an increased noise level in the acoustic shadow region behind the barrier.

For the numerical studies, a parabolic equation method (PE) is extended to model situations with a thin screen in a turbulent atmosphere. A scattering cross-section method is also extended to take into account source and receiver positions above a ground surface, and scaling properties are used to generate an efficient prediction scheme. A substitute-sources method (SSM) is developed, which is numerically faster than the PE. Both two and three-dimensional implementations are studied, from which it is concluded that the sound level can be well predicted for a large variety of situations using a two-dimensional model.

The effect of turbulence increases with frequency and with enlarged geometry. The study concentrates on road traffic noise situations, where screens or buildings are used as noise barriers. The results show that the increase in sound pressure level caused by turbulence can be large at higher frequencies and significant as an A-weighted level.

Keywords: outdoor sound propagation, traffic noise, turbulence, random media, barrier, parabolic equation method, scattering cross-section, substitute sources, numerical modelling, measurements.

Sammanfattning

Numerisk modellering och mätningar har använts för att studera hur atmosfärisk turbulens minskar ljudreduktionen hos bullerskärmar. Turbulensen orsakar ljudspridning vilket leder till en ökad bullernivå i den akustiska skuggzonen bakom en skärm.

För de numeriska studierna har en metod med parabolisk ekvation (PE) vidareutvecklats för att modellera situationer med en tunn skärm i en turbulent atmosfär. En spridningstvärsnittmetod har vidareutvecklats till att kunna ta hänsyn till käll- och mottagarpositioner ovan ett markplan, och skalningsegenskaper har använts för att utveckla ett effektivt beräkningsschema. En metod med ersättningskällor (SSM) har utvecklats, vilken är snabbare än PE-metoden. Både två- och tredimensionella implementeringar har studerats och slutsatsen därav är att ljudnivån kan förutsägas väl med en tvådimensionell modell för många olika situationer.

Effekten av turbulens ökar med frekvensen och med förstorad geometri. Detta arbete är koncentrerat på trafikbullersituationer där plank eller byggnader används som bullerskärmar. Resultaten visar att ökningen i ljudtrycksnivå på grund av turbulens kan vara stor vid högre frekvenser och betydelsefull i A-vägd nivå.

Papers appended

This thesis is based on the work contained in the following papers:

Paper I. Calculation of sound reduction by a screen in a turbulent atmosphere using the parabolic equation method. *Acustica*, Vol. 84, No. 4, pp. 599-606 (1998).

Paper II. Influence of atmospheric turbulence on sound reduction by a thin, hard screen: A parameter study using the sound scattering cross-section. Proc. 8th Int. Symp. on Long-Range Sound Propagation, The Pennsylvania State University, USA, pp. 352-364 (1998).

Paper III. Barrier noise-reduction in the presence of atmospheric turbulence: Measurements and numerical modelling. Submitted to *Applied Acoustics*, November 2000. (Coauthor Mikael Ögren. The work was shared equally between the two authors.)

Paper IV. Calculation of noise barrier performance in a turbulent atmosphere by using substitute sources above the barrier. *Acustica*, Vol. 86, pp. 269-275 (2000).

Paper V. Calculation of noise barrier performance in a turbulent atmosphere by using substitute sources with random amplitudes. Proc. 9th Int. Symp. on Long-Range Sound Propagation, The Hague, Netherlands (2000).

Paper VI. Calculation of noise barrier performance using the substitute-sources method for a three-dimensional turbulent atmosphere. To be submitted.

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Contents

1 Background

Traffic that causes high noise levels in residential areas is a widespread source of annoyance. Screens and buildings along the roadside are used as barriers to reduce the levels of traffic noise. Other measures which can lead to substantially lower traffic noise levels are to reduce either the traffic flow or the noise emitted by the source; today this is mainly due to the road-tyre contact of the vehicles.

To achieve an acceptable balance between noise level and transportation, it is reasonable that a combination of measures be used, such as barriers, tunnels, traffic control and less noisy vehicles.

For city planning purposes, it is desirable to have accurate predictions of whether a planned screen or building will give sufficient noise reduction. For this, the prediction methods must take into account the influence of wind, temperature gradient, and atmospheric turbulence. An irregular sound speed profile may reduce the barrier performance, while the atmospheric turbulence causes scattering of sound into the shadow zone formed by the barrier, thereby reducing its protection.

The problem investigated in this thesis is the influence of turbulence scattering on the sound reduction obtained with barriers. A specific situation of interest is the use of large buildings as road traffic noise barriers. The side of a building facing away from the street could then be a quiet one with a good noise environment.

In an urban area, there are usually many possible transfer paths for noise, for instance multiple reflections between buildings. In this thesis, however, isolated situations are studied, with a single barrier and without reflections from surrounding buildings. Moreover, since the scattering by turbulence is known to be stronger for smaller angles, i.e. for flatter geometries, a path for the noise to be reflected from a nearby building to the quiet side may well determine the noise level there. The models studied in this thesis are not limited to isolated situations; they can be made to model the effects of a more complex sound field, for example due to reflections in surrounding buildings.

It is very computationally demanding nowadays to calculate the whole problem directly by using a complete discretisation including the source, receiver, barrier, surrounding air, and ground surface (e.g. by using a finite element or a finite difference method). Hence, it is of interest to study and develop faster methods which model well the main physical processes that determine the results for the specific situations being studied. To devise such methods and study the influence of turbulence were the main tasks of the work underlying this thesis.

The thesis consists of an introductory part, Chapters 1–6, and Papers I–VI. Next follows a short introduction to sound propagation outdoors, Chapter 2. Chapter 3 summarises and draws conclusions from a literature study presented in the appendix. In Chapter 4 the methods used for the work are described. Chapter 5 contains discussion and conclusions.

2 Introduction to outdoor sound propagation

A sound wave that propagates outdoors is determined by the acoustic properties of the ground surface, the shape of the terrain, the air, and the sound source. Uneven variations in the terrain, such as screens and walls, cause reflection, diffraction, and may cause absorption. Smooth variations can also have these influences, but in a less distinct way. The acoustic impedance and the roughness of the ground surface determine its reflective properties and absorption. A wind or a temperature that varies with height generates a sound speed profile that causes curved ray paths, i.e. refraction. Local inhomogeneities in the air, such as turbulence, cause scattering and decorrelation of the sound waves. Other climatic phenomena, such as fog and precipitation, also influence the sound propagation. The molecular composition of the air, influenced by the temperature and humidity, determines the absorption.

The properties of sound propagating in an outdoor environment are largely influenced by the shape of the sound speed profile. When the sound speed increases with height, i.e. has a positive gradient, a sound wave refracts downwards and may repeatedly reflect against the ground surface as it propagates. Normally, this leads to a smaller attenuation of the sound than a sound speed profile with a zero gradient. Downward refraction occurs when there is a strong wind from the source toward the receiver, resulting in a large positive wind gradient that makes the sound speed increase with height. In calm weather, a positive temperature gradient (usually at night-time) also causes downward refraction. When the speed of sound decreases with height, there is upward refraction and shadow zones with largely attenuated sound fields. Such refraction occurs when sound propagates against the wind or when there is a negative temperature gradient, as is typical during the day.

The ground surface is usually modelled as an impedance plane. A good approximation for most ground surfaces is that they are only locally reacting, i.e.

there is no extended reaction to a point force. The impedance is then independent of the angle of incidence, and the calculations are much less difficult. When an incident acoustic wave propagates nearly parallel to a ground surface (i.e. near grazing incidence) with finite impedance, the reflection factor will be close to -1. Hence, for geometries where the source and the receiver are close to the ground, the direct and reflected rays interfere negatively.

As explained by Attenborough *et al*. (1994), the total path lengths of both the direct and reflected rays are modified in the presence of an irregular sound speed profile. For downward refraction the grazing angle becomes greater, hence the reflection coefficient deviates more from the value -1. Negative interference between direct and reflected waves then decreases and geometrical interference is shifted to higher frequencies. For upward refraction, the grazing angle becomes smaller and the reflection coefficient moves closer to -1. Negative interference between direct and reflected waves is strengthened and geometrical interference is shifted to lower frequencies.

For a screen in a homogeneous atmosphere, i.e. without refraction and turbulence, the properties of both the ground and the screen influence the sound transmission from the source to the receiver. Adding absorbing materials to the faces of the screen reduces the sound transmission notably only when either the source or the receiver position is close to the screen (L'Esprance *et al*., 1989). When the distances are greater, the properties of the top of the screen are more influential. For sound propagation above hard ground, which weakly attenuates the sound, the effects of screens become more dominant. In a refractive atmosphere, the curved wave paths can strongly change the effect of a noise barrier. A barrier can also alter the sound speed profile, due to the change in the air flow around the barrier. Salomons and Rasmussen (2000) have recently started to investigate this effect.

From an acoustician's point of view, the atmospheric turbulence can be seen as weak random fluctuations in wind and temperature that cause distortion of the sound waves. In an outdoor environment, atmospheric turbulence is almost always present. Although the strength of the turbulence varies, it always affects the sound wave if the propagation distance is long enough. One effect of the random medium fluctuations is the decorrelation for line of sight propagation, as between direct and ground reflected waves. Another effect is the scattering of sound into acoustic shadow regions which may be formed by barriers or by upward refraction. The scattering causes higher noise levels in the shadow regions.

3 Current prediction methods

Analytical solutions are available for acoustic situations with a constant complex-valued impedance boundary, a monopole source, and some sound speed profiles (e.g. linear) that vary only with height. The numerical methods can be divided into three groups, the first of which consists of ray-based solution methods. Since these are computationally fast, in general, compared with the other groups, they are used in softwares that can predict noise levels from many sources at many receiver positions. For example, the desired result could be a noise map of a city, showing how the traffic noise levels depend on location.

The second group of numerical methods contains more accurate approaches: the parabolic equation method (here abbreviated PE) and the fast field program (FFP). Due to the larger computational demands, the PE and the FFP have mainly been implemented for two-dimensional problems, where the solution is for height and range only. The FFP gives accurate results for any point in space. A range dependent ground property or medium cannot, however, be modelled directly in the FFP. Either range independent parts have to be coupled or a field due to objects inserted can be added. The PE is directly applicable to range dependent situations, but it gives a correct solution only up to a limited angle from the ground. In the PE, a turbulent atmosphere is modelled by an index of refraction that varies in height and range. As this range variation is not suitable for the FFP, the PE is usually more useful for predictions of turbulence effects. For a high barrier, neither the PE or the FFP is directly applicable. The FFP requires that the range dependency be dealt with, while the PE has the limitation that the accuracy decreases at wide angles. Also, the PE describes a wave emanating from the source; when a reflection from a barrier is of importance, it has to be calculated separately and then added to the solution.

The third group contains methods that solve the full wave equation in a discretised space, and all details of the medium or the boundary are taken into account. In the finite element methods (FEM), the whole space is discretised, whereas in the boundary element methods (BEM), the whole boundary is discretised. Usually these methods are implemented for frequency domain solutions, but time domain implementations are also possible. Since these calculation methods usually demand very large computational resources, they are used mainly for specialised problems, for example with two-dimensional models, for low frequencies or for small geometries. Similar to FEM are the finite difference implementations and the transmission line modelling.

There is also a large variety of approaches or methods that do not belong distinctly to any of the three groups described above. These are primarily hybrid methods, based on combinations of the others. The hybrid methods are usually applicable to specialised problems.

Atmospheric turbulence causes decorrelation, which affects the mean power of a received sound signal in situations with two or more contributing sound waves. The mean power can be calculated using the mutual coherence function (MCF) or transverse coherence function. The MCF for a homogeneous and isotropic turbulence was developed by Karavainikov (1956) for a Gaussian turbulence model, and by Ishimaru (1997) for the physically more correct Kolmogorov turbulence model. Various acoustic properties that take into account the movements in a turbulent medium were developed by Ostashev *et al*. (1997a and 1997b) and Ostashev (1997). The specific situation of coherence between direct and ground reflected waves was solved by Clifford and Lataitis (1983), and extended by Salomons (1998a) and Ostashev *et al*. (2000).

For scattering due to atmospheric turbulence, the single-scattering approximation is usually applied. A cross-section for the mean scattered sound power was worked out by Tatarskii (1971), and further developed by Ostashev (1997). In addition, the sound pressure from a single scattering object can be used for predicting the mean scattered power (the scattering by turbules-model presented by McBride *et al*., 1991 & 1992), as described in the appendix.

For a general acoustic situation with strong multiple scattering, an approach usually called the diagram technique can be used; it is also related to what is known as the transport equations (see e.g. Ostashev, 1997 or Rytov *et al*., 1989).

4 Solution methods

4.1 Description of the methods

In the work upon which this thesis is based, measurements and physical modelling have been used to investigate the influence of a turbulent atmosphere on the sound reduction obtained with a barrier. For the physical modelling, three methods have been used: A parabolic equation method (PE), a scattering cross-section method, and a substitute-sources method (SSM).

The versatility and accuracy, as well as the computational demands, vary among the methods. These qualities are discussed next.

Turbulence description

Turbulence can be variations in temperature and velocity, which occur naturally in the atmosphere. As turbulence variations are chaotic functions of time and space, they are usually described by their statistical properties.

Atmospheric turbulence can be described by the wave number spectra of the temperature and wind velocity fluctuations in space, and assuming they have random phases with uniform probability density. Usually, the temperature and wind velocity fluctuations are modelled with the same spectrum, although they have different amplitudes. The spectra used here are the Gaussian (Papers I, IV, V) and the Kolmogorov (Papers II, III, VI). A Gaussian spectrum is mathematically simple but can be adjusted to fit only a part of the physically correct turbulence spectrum; in contrast, the Kolmogorov spectrum is physically correct for a larger range of the turbulence wave numbers (see Wilson, 1994). A modification of the Kolmogorov spectrum to approximate the whole wave number range is the von Kármán spectrum. One can see the size, D, of a turbulence eddy as determined by the wave number, k, according to $D = 2\pi/k$. The deviation from the mean atmosphere of the eddy, in temperature or velocity, is described by the amplitude of the spectrum at k.

In the work presented here, the turbulence is assumed to be homogeneous and isotropic. This means that the statistics of the turbulence are independent of both position and rotation. These assumptions simplify the description of the turbulence and the calculations of its effects. To make predictions for more specific cases, it could be of interest to model the turbulence as locally homogeneous, i.e. with strength depending on position. Moreover, the turbulence scales that are comparable in size to their distance from the ground surface, or other boundaries, are not correctly described by an isotropic turbulence. Another interesting property of the turbulence is its intermittency, which can be described as an irregular variation over time of the turbulence strength.

The parabolic equation method (PE)

The parabolic equation method (known as PE) has previously been implemented for a thin screen (Salomons, 1994) and for situations including a turbulent atmosphere (e.g. Gilbert *et al.*, 1990). A method for considering a combined situation, a thin screen in a turbulent atmosphere, is developed in Paper I.

The PE method is derived from the Helmholtz equation and solves, in the far field and near the ground, a wave propagating outward from a source. The back-scattered field is omitted and the solution is obtained by an algorithm that steps forward in range, starting with an initial vertical field at the source.

Usually, the PE method is implemented for two-dimensional situations (range and height), where independence is assumed for the angle of rotation about the vertical axes through the acoustic source. Many situations of interest can be modelled in two dimensions. However, when modelling turbulence as two-dimensional, some characteristics of the sound field are changed, such as the fluctuation strengths of the phase and the amplitude (Salomons, 2000). Calculated results do, however, indicate that the scattering into shadow regions is not altered significantly when a two-dimensional model is used instead of a three-dimensional one (Paper VI). A two-dimensional Crank-Nicholson finite difference implementation of the PE is used here, as in West *et al.* (1992).

The thin screen is represented by setting the pressure field equal to zero, from the ground up to the top edge of the screen, at the propagation distance of the screen, as previously done by Salomons (1994). This representation means that the reflective properties of the screen are not well defined, however a thin hard screen is well approximated in situations where the screen is low in relation to its distance from both the source and the receiver, as shown in Paper I.

The turbulent atmosphere is modelled by a randomly varying index of refraction in the two-dimensional space, according to Gilbert *et al.* (1990). That the turbulent atmosphere varies with time is modelled by applying the PE to many independent realizations of the index of refraction.

The scattering cross-section method

The sound scattering cross-section by Tatarskii (1971) is used to calculate the acoustic power scattered by the turbulence into the shadow zone behind the barrier. The power diffracted by the barrier, calculated separately for a homogeneous atmosphere, is added to the scattered power. This hybrid approach was developed by Daigle (1982) for a thin hard screen, and is much less time consuming than the PE method.

The sound scattering cross-section is derived by assuming that, for each scattering angle, only a single wave number component of the turbulence produces the scattering. (This is similar to the Bragg planes used in optics for scattering by crystals.) A single scattering approximation is used, which means that the method is restricted to small fluctuations of the sound field; this limits the propagation range. Moreover, the Fraunhofer approximation is used, which allows the sound scattering from different points to be treated as uncorrelated.

The sound scattering cross-section is integrated over the volume in space where the main scattering is produced, thus summing the contribution from different angles, i.e. for different wave number components of the turbulence. The volume of integration is that above the barrier, which is in the line of sight from both the source and the receiver. When a ground surface is introduced, it is assumed that the ground-reflected and direct contributions by scattering are only partly correlated. In Paper III an approximate way to estimate this decorrelation is shown. Moreover, scaling properties were found and an efficient prediction scheme developed, by which a small set of tabulated data are used for calculating many different situations, Papers II and III.

The substitute-sources method (SSM)

The substitute-sources method (SSM) can be viewed as being based on the Rayleigh integral. The receiver's field, emanating from a source, is described as a superposition of fields from a distribution of sources placed on a plane surface. The surface is called the substitute surface, and the sources on the surface are the substitute sources.

If the substitute surface is located between the barrier and the receiver, there are free paths from all substitute sources to the receiver. The calculation of sound propagation along the free paths is possible for various types of inhomogeneous atmosphere. Here, a mutual coherence function (MCF) for a turbulent atmosphere is used. For the MCF, it is assumed that the correlation radius of the sound field is large compared with the wavelength, which limits the applicability to ranges of propagation that are not too long (Paper VI). The substitute-sources method is not limited to low angles as is the parabolic equation method (PE), and it is numerically much faster, at least for two-dimensional implementations, Paper IV. Compared with the scattering cross-section method, the SSM, while much slower computationally, is not limited by the single-scattering approximation. An advantage of the PE is that it is applicable to more general range dependent situations than the SSM, such as a varying terrain profile or ground impedance. Moreover, a limiting assumption of the SSM is that the atmosphere is homogeneous on one side of the barrier. The largest error due to this assumption is expected to occur when the distance between source and barrier equals that between barrier and receiver. For other situations, the homogeneous atmosphere should be designated as the side with the shorter of the two distances.

Measurements

Experimental studies of turbulence effects on the sound reduction obtained with a barrier were made by Daigle (1982). A similar measurement setup was used here, Paper III. The atmospheric turbulence is measured at a single point in space and homogeneous and isotropic turbulence is assumed. Also, the *frozen turbulence* hypothesis is used, which implies that the time variations measured at a single point are equivalent to the spatial variations along the direction of the mean wind. The measurements presented in Paper III are for a thick barrier of a greater height than in Daigle's measurements, which results in significant turbulence-scattering effects at lower frequencies. The sound pressure at various receiver positions was measured simultaneously with the turbulence. The acoustic source was small in order to approximate a point source, while the source signal was a random noise. The turbulence can be measured with either a hot-wire or an ultrasound anemometer. The range of turbulent scales that can be measured depends on the type of equipment. When the ultrasound anemometer is used (as in Paper III), only the larger scales can be measured; the spectrum is extrapolated assuming the Kolmogorov model. To measure smaller scales, a hot-wire anemometer can be used. The measured strengths of the velocity and temperature turbulence were used as input to the scattering cross-section method, as well as to the estimation of the decorrelation effects on both the scattered and the diffracted fields.

4.2 Application of the methods

In Paper I the PE method is used to study situations where it is applicable, i.e. for flat geometries, where the screen is low in comparison to its distance to the source and receiver. The results are compared with those from using the sound scattering cross-section method. In Paper II the sound scattering cross-section method is the only one used. A parameter study is carried out, with the aim to determine in what situations a turbulent atmosphere significantly influences the sound reduction by a thin, hard screen. The scattering cross-section method is extended, in Paper III, to take into account a ground surface and elevated source and receiver positions. The results are compared with those from a controlled outdoor experiment with a thick barrier.

The substitute-sources method is studied in Papers IV–VI. In Papers IV and V a two-dimensional implementation is used for examples with flat geometries, i.e. when the screen is low in comparison to its distance from both the source and the receiver. For flat geometries, the Kirchhoff approximation can be used, which simplifies the calculation of the strengths of the substitute sources. In Paper IV the results are compared with those in Paper I, from the parabolic equation method (PE). Random realizations of the strengths of the substitute sources are used for modelling the effect of a turbulent atmosphere, see Paper V. The dependence of a varying screen height is also studied.

In Paper VI a three-dimensional substitute-sources method for steep geometries is developed. The Kolmogorov turbulence model is used and the results are compared with those from a two-dimensional implementation and from the scattering cross-section method.

5 Discussion and conclusions

The scattering cross-section method is numerically faster than the PE and SSM, and the results were shown to agree fairly well with measurements for a variety of situations over a broad frequency range. The agreement with PE results were also within reason. The above supports the usefulness of the scattering cross-section method. However, the method involves some simplifications: the single scattering approximation, the independence of the scattering from the barrier diffraction, and modelling the scattering from different points as uncorrelated contributions.

The results from the two and the three-dimensional implementations of the SSM were very similar for all of the situations studied. Hence, the conclusion is drawn that the influence of atmospheric turbulence on the sound level in the shadow of a barrier can be well modelled in two dimensions for these and similar situations.

The PE was shown to agree well with the SSM for situations with flat geometries, where the PE is applicable. For steeper geometries also, the scattering cross-section method showed the same trend in the results as the SSM, namely that the influence of turbulence is strongest for lower screen heights. The results from the scattering cross-section method do, however, show a weaker influence of turbulence than the results from the SSM.

Since the PE and SSM do not involve simplifications as significant as those in the the scattering cross-section method, they should give more accurate results. When two-dimensional modelling is sufficient, the SSM is a useful method. When the Kirchhoff approximation is not used, the SSM is applicable to steeper geometries than the PE, and is faster as well. In conclusion, the scattering cross-section method can be useful when fast calculations are needed; otherwise, the SSM is more suitable. However, in flat situations, for example with range dependent ground properties, the PE would be needed.

As to the effects of the atmospheric turbulence, it was shown that the influence of the turbulence scattering on the sound reduction by a screen becomes stronger when the geometry is expanded in scale or when the frequency is increased. For large geometries, e.g. when a building is used as a noise barrier along the road side, it is concluded that taking into account atmospheric turbulence can significantly reduce the barrier performance for road traffic noise, not only at high frequencies, but also as an A-weighted sound pressure level.

Since the influence of turbulence was shown to be weak for relatively steep geometries, the noise level on the quiet side of a building is not expected to be directly influenced by the atmospheric turbulence. However, in an urban environment, reflecting and scattering objects behind the building would usually be present, for instance other buildings or an uneven terrain. Hence, the influence of turbulence on the sound field incident to these objects should be taken into account, especially since they are a part of a flatter geometry for which the turbulence influence is likely to be stronger. Similarly, noise contributions from distant roads may become greater when the turbulence effects are included.

The work presented in this thesis deals with an isolated part of an urban area. The noise level in a more general urban situation is influenced by many transfer paths, for instance multiple reflections between buildings. To predict the noise levels in shielded areas in such complex situations, further studies are needed. For future work it would also be of interest to model thick barriers, sound speed profiles and a finite impedance ground in the SSM. Moreover, it would be desirable to model the turbulence more closely, primarily its variations in strength that are changing with position and time. To make accurate predictions for individual situations, appropriate data for the turbulence strength are needed.

The unique features that characterize this thesis can be described as follows. A parabolic equation method was further developed, and situations with a thin screen in a turbulent atmosphere were studied. A scattering cross-section method was extended to take into account source and receiver positions above a ground surface. Also scaling properties were found and used to generate an efficient prediction scheme. Measured results including the atmospheric turbulence were obtained for situations with a thick barrier as well as elevated source and receiver positions. A substitute-sources prediction model was put together. Implementations were made for both two and three-dimensional problems, and a variety of situations were examined. An implementation using random realizations of the strengths of the substitute sources was studied as well.

Appendix. Literature study

Methods to predict the sound pressure level in outdoor situations were reviewed to identify what problems can be solved today. Methods that may be used for situations involving a sound barrier or a turbulent atmosphere are of special interest. The models underlying each method are described briefly, as well as its performance. The first two sections deal with analytical and numerical solutions for situations without a barrier; the last section treats situations including a barrier.

1. Analytical solutions

Analytical solutions are available for situations with a constant complex-valued impedance boundary, a monopole source, and some sound speed profiles (e.g. linear) that vary only with height. For a locally reacting ground surface with constant properties over distance, there are multiple models for finding the acoustic impedance, for example the commonly used one-parameter model by Delaney and Bazely (1970), or another by Attenborough (1985). The ground reflected wave from a finite-impedance ground surface is usually calculated using a spherical reflection coefficient (Chien and Soroka, 1975), or a cylindrical reflection coefficient if a line source is modelled. These solutions are approximations for near-grazing incidence, i.e. for low source and receiver heights.

Analytical ray-tracing and other methods

For a linear sound speed profile, a closed form solution for the acoustic rays can be found; it is usual in ray-tracing models that a non-linear sound speed profile be approximated as linear (Attenborough *et al.*, 1994). In general, ray models are high frequency approximations. It was furthermore explained by Attenborough *et al.* (1994) that there is no general ray-tracing solution for the situation with many ground reflected paths, i.e. at longer ranges of downward refraction. For upward refraction, ray theory predicts total silence in the shadow zones. Numerical ray-tracing algorithms can be applied to more general situations.

Raspet *et al*. (1991) investigated upward refraction using a residue series solution of the sound field, represented in terms of Airy functions, and showed the importance of the surface wave contribution to the shadow zone. Sound propagation in a downward refracting atmosphere using a normal modes analysis was also examined, Raspet *et al*. (1992). The role of the surface wave was explained. The relation of sound propagation to the interaction between the refracted sound and the finite-impedance ground surface was also studied.

Solutions for a turbulent atmosphere

A turbulent atmosphere causes decorrelation and scattering of the sound. The decorrelation influences the mean power of a received signal coming from two or more sources. This is described with what is usually called the mutual coherence function (MCF) or transverse coherence function. The MCF for a homogeneous and isotropic turbulence was developed by Karavainikov (1956) for a Gaussian turbulence model, and by Ishimaru (1997) for the physically more correct Kolmogorov turbulence model. Various acoustic properties that take into account the movements in the turbulent medium were found by Ostashev *et al*. (1997a and 1997b) and Ostashev (1997). The specific problem of the coherence between direct and ground reflected waves was solved by Clifford and Lataitis (1983), and refined by Salomons (1998a) and Ostashev *et al*. (2000).

For the scattering caused by atmospheric turbulence, the single-scattering approximation is usually applied. A scattering cross-section for the mean scattered sound power has been developed by Tatarskii (1971), and advanced by Ostashev (1997). The scattered sound pressure from a single scattering object can also be used for predicting the mean scattered power, as described in the next section.

For a more general situation, with strong multiple scattering, an approach usually known as the diagram technique can be used; this is related to transport equations (see e.g. Ostashev, 1997 or Rytov *et al.*, 1989).

Approximate solutions

The approximate solutions are generally used for finding numerically fast prediction methods. L'Esprance *et al.* (1992) used a heuristic model based on an extension of the geometrical ray theory. The effects of curved ray paths and the loss of coherence due to turbulence were included. The model assumes a linear sound speed profile, and comparison with measurements showed that this simplification is acceptable as a first approximation for propagation distances up to 1 km.

Kai Ming Li (1995) presented an asymptotic analysis for long ranges, for an arbitrary downward refracting sound speed profile. The solution can be expressed in a Weyl-Van der Pol formula, which is derived from the asymptotical limit of the wave equation represented in terms of Airy functions. The method was shown to be similar to the heuristic model presented by L'Esprance *et al.* (1992).

Salomons (1998b and 1999) developed a fast calculation method for downward refraction above a finite-impedance ground. The method is based on ray theory and models the effects of caustics in an appropriate way, including the diffraction fields in caustic shadow regions. At a caustic the sound rays are focused, which causes the amplitude to tend to infinity according to geometrical acoustics theory.

In recent years, many general traffic noise prediction models based on geometrical ray theory have been generated. The aim of these is an easy-to-use software that can predict traffic noise levels in residential areas. An example of such a model is the one being developed in the Nordic countries. The refraction, obstacles and ground properties are taken into account in approximate ways (see e.g. Plovsing, 2000). The predictions are for third-octave bands and the results may be presented as a noise map of the area of interest.

2. Numerical methods

Parabolic equation models

Under the restraint that the sound propagates cylindrically and in only one direction (i.e. outward from the source), the governing equation is a parabolic partial differential equation, which can be solved by standard numerical methods. A vertical starting field at the source is evolved step-wise toward the receiver, and the solution will be correct only within a limited angle from the ground. The parabolic equation model can be used to solve for an arbitrary sound speed profile, an arbitrary range-dependent atmosphere or ground impedance, terrain profiles, and propagation over screens; it can also model turbulence as snapshots of fluctuations in the medium (Attenborough *et al.*, 1994).

The parabolic equation method (PE) was originally implemented for sound propagation under water. In the first work where the PE is applied to outdoor sound propagation, by Gilbert and White (1989), it is used for a situation with only a vertically varying sound speed, thus not including turbulence effects. The numerical results from the wide-angle, finite difference implementation show good agreement with measured data for downward refraction. For high frequency upward refraction, the exclusion of turbulence leads to inaccurate and extreme shadowing.

West *et al.* (1992) also solved the parabolic equation using a finite-difference technique. The use of what is know as a Gaussian source, as an approximation for the true cylindrical or spherical source, was shown to lead to an error in the solution which is most prominent near the source, however it is negligible further away.

Gilbert and Di (1993) formulated and solved the PE with the Green function method (GF-PE) involving FFT. The GF-PE is said to be much faster than any finite difference scheme PE. Apart from that, it is not shown in the article whether the GF-PE differs in any other way from other PE solution methods.

Gilbert *et al*. (1990) included a two-dimensional turbulence model in the PE, by using a fluctuating stochastic index of refraction following a Gaussian distribution. Independent realisations (snapshots) of the index of refraction are generated and the propagation through each realisation is computed. The mean power of the sound signal is calculated from a large set of realisations. The solution in the paper was found for an upward refracting atmosphere using a finite difference PE method. It was concluded, for frequencies above a few hundred hertz, that sound scattered by turbulence dominates the sound in the shadow zone. Di and Daigle (1994) included turbulence in the GF-PE method. The numerical results for upward refraction showed shadow zone attenuation of 15–30 dB relative to free field, which agreed with measurements.

Stinson *et al*. (1995) compared predictions made with the GF-PE method, including scattering by turbulence, with data measured in a range of 700 m at a quiet airfield. The comparison was made for upward refraction conditions; after adjusting the correlation length and the strength of the turbulence refraction, the numerical results showed good agreement with the measurements. Unfortunately, one cannot confirm that the values of the turbulence parameters adjusted to fit the data were representative for the measuring conditions. However, it was stated that the values used in the calculations were not atypical.

Chevret and Blanc-Benon (1995) compared measured data with predictions calculated according to the PE model, including turbulence effects. A better agreement with measurements was shown when the scattering by turbulence was included, not only for shadow zones, but also for interference regions, where phase decorrelation between the direct and the ground reflected waves leads to a weaker, and more realistic, destructive interference.

Chevret *et al*. (1996) demonstrated a way to describe the turbulence by random Fourier modes. Problems with upward refraction and without any refraction were studied; the solutions were in good agreement with measured data. To achieve better agreement, it was proposed that when modelling the turbulent atmosphere, one should account for the vectorial character of the turbulence, which should be easy using the random Fourier modes. This included that the commonly used Gaussian spectrum of the turbulence should be exchanged for the von Kármán spectrum. The smaller scale turbulence will then become stronger, which is in accordance with turbulence theory and measurements.

When Juvé *et al*. (1994) used a von Kármán spectrum, there was better agreement with measurements for upward refraction. Although the vectorial character of the turbulence was introduced, it did not appear to improve the agreement with the measured data.

Stinson *et al*. (1994) used the GF-PE method, including turbulence, for calculation of the sound attenuation into a shadow zone, for upward refraction. It was shown that the contribution by turbulence scattering in the shadow zone is dominated by scattering from a relatively small region, midway between source and receiver, and at turbulence length scales of 2 to 5 m, for the frequency 500 Hz.

Sack and West (1995) presented a PE method that, by means of a transformation, can solve for an arbitrary but smooth terrain profile, in a homogeneous atmosphere. West (2000) has further refined the PE so that an arbitrary terrain profile, including backscattering from steep obstacles such as barriers, can be modelled. Craddock and White (1992) described a PE approach that includes a range dependent surface impedance. Only problems with a homogeneous atmosphere were solved. In a Ph.D. thesis by Galindo Arranz (1996), various aspects of the finite difference implementation of the PE were studied extensively. The modelling of a point source was improved using a back propagated starting field. Ostashev *et al*. (1997c) proposed a way to more accurately account for wind velocity components when deriving the wide-angle PE.

Models using the fast field program (FFP)

The fast field program (FFP), which solves the wave equation in horizontal layers, is not restricted to low angles and outward propagating waves, as the PE is. The FFP can solve for sound propagation only in a range independent medium, over a range-independent ground surface, for an arbitrary sound speed profile. A turbulent atmosphere cannot be directly incorporated, since it must be modelled by a medium that also changes with range. This method solves the exact representation of the sound field for each layer in the horizontally stratified atmosphere; an FFT algorithm is used for solving the integral equations that arise. Various implementations of the method permit different ground properties (Attenborough *et al.*, 1994).

L'Esprance *et al.* (1993) compared measurements with results obtained from FFP calculations, including measured ground impedance and wind speed profile. For downward refraction, the numerical results are stated to be in impressive agreement with the measurements. For upward refraction, the exclusion of turbulence scattering leads to shadowing that is too strong.

Y. L. Li (1995) presented an extended FFP, with which an arbitrary, continuous, height-dependent refractive index profile can be used, instead of a horizontally stratified atmosphere. A Wentzel-Kramers-Brillouin-type (WKB) approximation with Airy functions was applied and the computation time was dramatically reduced in comparison with previously used FFP methods.

Raspet and Wu (1995) used analytical expressions for the decorrelation of the different wave number components caused by a turbulent atmosphere and incorporated them in the FFP. The decorrelation between direct and ground reflected waves was estimated (in a way similar to L'Esprance *et al.*, 1992) by determining the maximum path separation between the wave number components. The results from the model were shown to agree with measured data, for both upward and downward refraction. However, the model does involve significant approximations. For instance, finding the maximum path separation is not a straightforward task and is itself subject to approximations. Nevertheless, this procedure is shown to be better than the model used by L'Esprance *et al.* (1995), where only the sound speed profile is assumed to be stochastic, i.e. a one-dimensional turbulence model.

Range dependence could be modelled by a hybrid approach where boundary element (BE) calculations are coupled to the FFP calculations, as proposed by Taherzadeh *et al.* (2001). Schmidt *et al.* (1995) presented a way to apply the FFP to range dependent problems so that situations in ocean environments could be studied. The medium and boundary are divided into range independent sectors, called super-elements, and the solution is obtained by matching the boundary conditions between the sectors.

The Gaussian beam approach

The basic idea of the Gaussian beam approach is to launch a fan of beams from the source and trace them numerically through the medium, according to the ray tracing theory. Since the predictions give average results, they are not sensitive to the exact details of the medium. Using the Gaussian beam approach, Gabillet *et al*. (1993) showed good results for downward refraction. For upward refraction, however, the results are worse than those from an FFP method. A scenario with a thin screen and downward refraction was solved and compared with measurements from a laboratory set-up. Good agreement between predicted and measured levels was shown.

Other methods

In the scattering by turbules-model, the turbulent atmosphere is described as a set of scattering objects, called turbules. The scattered pressure from each turbule is summed at the receiver position. The statistical properties of the total scattered pressure are obtained from many realisations with randomly distributed turbules. McBride *et al*. (1991 & 1992) developed this model and applied it to line of sight propagation (1991) and upward refraction (1992), showing good agreement with measured data. Goedecke and Auvermann (1997) extended the theoretical basis of the model. For instance, they showed that in the inertial range of the turbulence, the scattering is independent of the distribution of the index of refraction inside each turbule.

A quite original approach to solving problems including refraction and turbulence has been introduced by Ostashev and Wilson (2000). In their approach, a numerical scheme similar to the one used for the sound pressure in the finite-difference PE is used for the mean sound power, including the turbulence decorrelation.

Some propagation problems can be successfully divided geometrically into an analytically solvable volume and a volume that needs to be discretised before being solved numerically. This can be called a hybrid approach. For instance, a volume containing a source and a barrier can be discretised and solved by a boundary element method (BEM) or a finite element method (FEM). The solution calculated at the boundary of the volume can then be used to determine the field outside the volume. For an example of the use of this approach, see Jean (2000).

In what is known as transmission line modelling (TLM) (see Kristiansen, 2000), a calculation is made for how a pressure pulse propagates over time in a spatial grid. Each node of the grid has known reflection and transmission properties for the pressure pulses that come through the lines of the grid. Other time domain solution methods have been suggested, for example using finite difference algorithms (Shum *et al.*, 1999).

3. Propagation over screened ground

There exist various approximate solutions in the frequency domain for a thin semi-infinite screen with a straight edge. The solutions are for either a soft or a hard surface, i.e. for either pressure or velocity equal to zero on the surface. The commonly used solution methods for a thick barrier are based on the thin screen solutions (see e.g. Salomons, 1997). It should be noted that, since a semi-infinite screen is assumed, the results would be erroneous for a screen on a reflecting ground unless the screen is high enough in comparison with the wavelength. This can be caused by strong higher order diffraction terms; the wave diffracted from the edge of the screen is reflected in the ground surface and diffracted again at the screen edge, which generates an additional pressure wave to the receiver.

It was shown by Daigle (1989) that a curved surface (e.g., a curved berm) improves the high-frequency sound reduction more than a thin screen with the same effective height. (The effective height is the distance from the ground to the lowest point above the screen that is in the line of sight for both the source and the receiver. Thus, for a thin screen, the effective height is the height of the screen.) It was also shown that a slow waveguide fitted in a thick barrier reduces the transmission for a restricted frequency range and increases the transmission elsewhere.

Salomons (1994) published results of a PE method for diffraction by a screen in a downward refracting atmosphere. The high frequency results for the barrier insertion loss fluctuate widely when the wind speed is increased. At a lower frequency, the solution was more stable, and the insertion loss slightly increased with wind speed.

Daigle (1982) published numerical results for diffraction by a thin screen in the presence of atmospheric turbulence. In his model the acoustic power arising from turbulence scattering is added to that diffracted by the screen. When the sum of the two contributions was compared with measured data for different situations, the agreement was better than for diffraction theory alone, especially at higher frequencies and for large screen to receiver distances. The theory for the scattering, which comes from Tatarskii (1971), assumes a locally homogeneous and isotropic turbulence, and is a single scattering approximation that requires large enough scattering angles.

Concerning the shape and material of a sound barrier, much effort has been made to optimise the top of the barrier. Hothersall *et al*. (1991) used a boundary element method to calculate the sound reduction of three barrier shapes: T-, Y- and arrow. The results show mainly that the effective height of the barrier is a more relevant sound reduction parameter than the actual height.

Hasebe (1993) measured and calculated the sound reduction by a T-shaped barrier. The numerical results were based on diffraction theory for which both edges of the barrier top were included. The numerical results were in good agreement with measurements and it was shown that a T-profile barrier performs better than an ordinary thin barrier of the same height (which is in agreement with the results above, by Hothersall *et al*. (1991), that the effective height is the determining reduction parameter).

Möser (1995) presented numerical realizations of analytical solutions for a screen with a cylinder attached to the top. The impedance of the cylinder was varied and, as an example, the performance of a cylinder acting as a Helmholtz resonator was chosen, where the sound reduction increased in the neighborhood of the resonance frequency. For measured results also, see Möser and Volz (1999).

Salomons *et al*. (1997) applied a Fourier-boundary element method (Fourier-BEM) to three-dimensional traffic noise situations (two-dimensional geometries and a point source). For instance, interesting cases with double screens were investigated.

Salomons (1997) derived an approximate three-dimensional model by which the diffracted or reflected field from one object is put together with the fields from other objects, thereby enabling predictions for complex situations with many diffracting and reflecting objects.

Rasmussen (1996) investigated the effect of a screen in an upward refracting atmosphere. His hybrid approach is based on a model for a stratified atmosphere, similar to the FFP, and an analytical solution for the diffraction by the screen. The predictions showed reasonable agreement with measured data. When the wind blows, the flow of the air is changed if a screen is introduced. This causes a range-dependent sound speed profile, which affects the acoustic performance of the screen. These effects have been studied by Barriere and Gabillet (1999) and by Salomons and Rasmussen (2000).

The sound reduction obtained with a barrier can be calculated using the equivalent sources method. The barrier surface is then replaced by a fictitious surface, inside which are put sources that together fulfill the boundary condition on the surface. The sources inside the surface are called equivalent sources, and the sum of the pressures from each of these sources plus the pressure from the original sound source yields the resulting pressure at a receiver position. In the work by Thorsson (2000), the method is applied to an optimisation problem where the optimal surface impedance of the barrier is found with respect to the sound power in an area behind the barrier.

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