inter.noise HAMBURG 2016

Traffic with noise modeling consideration of meteorological effects

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ABSTRACT

Traffic noise may be greatly affected by wind and temperature variability due to the effect of atmospheric refraction. However such effect is not taken into account in popular traffic noise prediction models, albeit some models consider atmospheric absorption related to weather effects. A model is presented in this paper which combines the well established CoRTN traffic noise prediction model with an empirical atmospheric refraction model to compute the road traffic noise with meteorological effects included. Large eddy simulations are first performed in OpenFOAM to simulate the atmospheric flow in a typical urban setting. Grid refinement studies have been carried out, and a dynamic Lagrangian sub-grid model has been employed to ensure realistic wind and temperature fields are achieved. Time-averaged values of meteorological parameters including wind shear, wind speed, and lapse rates are obtained at the noise modeling observation points, and subsequently fed into the presented model. Numerical examples are presented for representative urban scenarios subject to meteorological effects, and the results are also compared against those where meteorological effects are not considered.

Keywords: Traffic noise, Meteorological effect, CoRTN I-INCE Classification of Subjects Number(s): 76.1

1. INTRODUCTION

Outdoor noise propagation is affected by atmospheric scattering, absorption, and refraction of acoustic waves. Compared to other atmospheric effects, refraction has a stronger impact on noise propagation (1). However the atmospheric refraction has not been taken into account in popular traffic noise prediction models such as CoRTN (2). An empirical atmospheric model is presented in (3), which is a function of wind shear, wind speed, and lapse rate. In this paper, we combine the empirical atmospheric refraction model and the CoRTN for three-dimensional (3D) traffic noise mapping with meteorological effects considered.

Prior to the application of the empirical atmospheric refraction model, it is necessary to simulate turbulent wind flows to obtain the required meteorological parameters. However within the built environment these simulations can become extremely challenging, with complex building layouts, distributed heating from anthropogenic and geophysical sources, and inhomogeneous land use and terrain all affecting the wind patterns (4). Even in the most simple of cities the wind flow will possess a wide range of spatial and temporal scales, the largest synoptic scales being $O(100\text{ km})$ and the smallest Kolmogorov scales being $O(1\text{ cm})$. To completely resolve such a range of scales – i.e. what is termed direct numerical simulation (DNS) – is unlikely in the foreseeable future, and thus alternatives must be sought (5).

For environmental flows, and indeed for most industrially related fluid problems, the Reynolds-averaged Navier-Stokes (RANS) approach has historically been adopted. Amongst other reasons, this is because of the ease and speed with which simulations can be constructed and performed. RANS simulations solve for the mean flow, while parametrizing any fluctuations about this mean (6). As these parametrizations are mostly developed for specific and idealized flows, their extrapolation to wildly different scenarios is a major source of inaccuracy. Large eddy simulations

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(LES) sit somewhere between DNS and RANS. Within an LES the large scales of the flow are computed explicitly, while the smaller or sub-grid scales are modelled (7). This means that, in principal at least, accurate unsteady flow computations can be performed in a domain where the exact urban environment is described. The penalty for this improved accuracy is increased set-up and computational time, however where accurate description of the turbulent flow in complex domains is required, LES is a necessity.

2. METHODOLOGY

2.1 Large Eddy Simulations (LES)

As previously stated, in LES the larger scales are computed explicitly while the smaller scales are modelled. In practice this is done by applying a filtering operation on the prognostic variables at a length scale Δ (typically grid scale), thus representing instantaneous values as the sum of filtered and non-filtered components. After performing this operation, the equations to be solved within LES are the filtered continuity and Navier-Stokes equations, written in Cartesian form as

$$\frac{\partial \widetilde{u}_i}{\partial x_i} = 0 \tag{1}$$

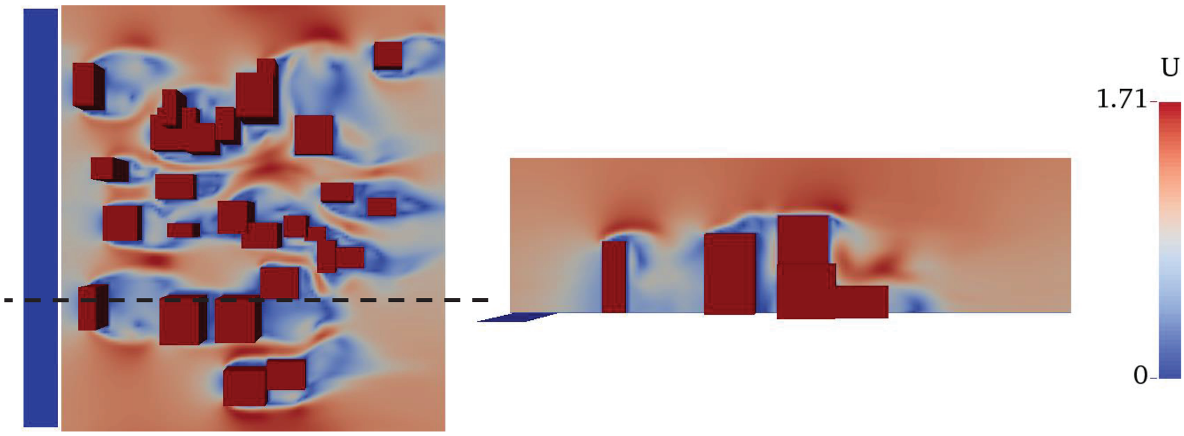
and

$$\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial \widetilde{u}_i \widetilde{u}_j}{\partial x_j} = \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_j^2} - \frac{1}{\rho_0}\frac{\partial \widetilde{p}}{\partial x_i} - \delta_{i,3} g \frac{\widetilde{\theta}'}{\theta_0} - \frac{\partial \tau_{i,j}}{\partial x_j} \tag{2}$$

In the above, $\widetilde{u}_i$, $\widetilde{p}$, and $\widetilde{\theta}$ are the filtered velocity, pressure and temperature fields; ρ_0 and θ_0 are the basic state of the density and temperature fields used in the Buossinesq approximation for buoyancy; ν is the kinematic viscosity t is the temporal coordinate, g is acceleration due to gravity, $i = 1,2$ are the wall-parallel directions, and $i = 3$ is the vertical direction. The final term in equation (2), is the SGS stress tensor, and represents the effects of the smaller, sub-grid scales of motion on the resolved flow. It is the modelling of this term which is crucial to the accuracy of the LES technique (8). Within the current work the dynamic Lagrangian model developed by Meneveau et al. (9) has been applied. A major advantage of this model is that it can be applied to highly irregular domains, such as that found in urban environments, and does not require spatial heterogeneity to function well.

LES simulations were performed in OpenFOAM (10) on an idealized town of size 250 x 250m, located downstream of a busy road. The urbanised area consisted of 30 cuboids, the coordinates and dimensions of which were randomly generated. The minimum and maximum heights of the cuboids were 10m and 50m respectively, and the domain height was 300m. The coordinate system is such that the x and y directions are perpendicular and parallel to the road, respectively, and z is the wall-normal direction. A wind flow of magnitude 1m/s at z=40m was enforced in the x direction. Temperature boundary conditions of 306K were applied to the ground and building surfaces, and an initial ambient temperature was prescribed as 303K. The wind and temperature fields were integrated in time over a period of 80 minutes, and time-averaged fields were computed after discarding the initial 20 minutes of simulation time. The grid resolution on the buildings was a minimum of 10 points/edge in the horizontal directions and 20 points/edge in the vertical direction. This resolution, although coarse, has previously been shown by Tseng et al. (11) to be sufficient to accurately depict flow patterns over realistic urban geometries.

Instantaneous contours of the velocity magnitude are shown in figure 1. The solid blue rectangle to the left of the domain represents the location of the road. The figure shows how upstream buildings can act to deflect the oncoming wind, causing channelling and attenuation of the wind at different locations. These wind patterns greatly affect the propagation of sound from the road.



(a) (b)

Figure 1 – Instantaneous contours of the velocity magnitude taken from the LES simulation. Note that the solid blue rectangle indicates the position of the road. (a) Contour in the x-y plane at z=1m. (b) Contour in the x-z plane, plotted at the location indicated by the dashed line in figure 4(a).

2.2 Atmospheric Refraction Model

The atmospheric refraction model given by (3) is an expression in terms of wind speed (S), lapse rate (γ), and wind shear (τ). Lapse rate represents the ratio of the difference between the temperature at the higher and lower meteorological station to the vertical distance between the thermometers. Wind shear denotes the ratio of the difference between the wind vector in the propagation path between the anemometers at the higher and lower meteorological station to the vertical distance between the anemometers. The atmospheric refraction (ar) predicted by the model for each octave band is shown as follows:

63 Hz $$ar = 0.337 + 0.13S - 5.57\gamma^2 + 0.604\tau^2 - 0.0517S^2 - 1.78\tau\gamma \quad (3)$$

125 Hz $$ar = 0.468 - 4.99\gamma - 0.401S - 29\gamma^2 + 0.113S^2 - 0.199\tau S \quad (4)$$

250 Hz $$ar = 0.48 + 0.6\tau - 4.16\gamma - 0.394S - 26.6\gamma^2 + 0.0901S^2 - 0.296\tau S \quad (5)$$

500 Hz $$ar = 0.463 - 4.15\gamma - 16.8\gamma^2 - 0.0111S^2 - 2.94\tau\gamma + 0.725\gamma S \quad (6)$$

1 KHz $$ar = 0.62 + 0.828\tau - 4.26\gamma - 0.475S - 32.6\gamma^2 + 0.0961S^2 - 0.321\tau S \quad (7)$$

2 KHz $$ar = 0.612 + 0.625\tau - 3.07\gamma - 0.357S - 22.8\gamma^2 + 0.063S^2 - 0.226\tau S \quad (8)$$

4 KHz $$ar = 0.406 - 0.224\tau - 2.59\gamma - 11.4\gamma^2 - 2.96\tau\gamma + 0.0834\tau S + 0.777\gamma S \quad (9)$$

8 KHz $$ar = 0.382 + 0.00811\tau - 0.199\gamma - 0.00854S - 0.0925\gamma^2 + 0.0201\tau^2 - 0.0301\gamma S \quad (10)$$

2.3 Noise Prediction

An algorithm based on the CoRTN (2) is developed for noise prediction and mapping due to geometrical spreading (12). The search angle method is employed, which divides the road line sources into small segments and searches them one by one. The roads are classified into five categories with assumed values of basic noise level at a distance of 10 m away from the nearside carriageway edge. The noise level due to distance attenuation, unobstructed propagation (ground absorption) effect, obstructed propagation (screening) effect, and site layout effects is calculated according to the CoRTN method. An efficient algorithm is developed for checking if the road line sources are obstructed by buildings and other obstacles (12).

3. NUMERICAL EXAMPLES

3.1 Validation of the Refraction Calculation

The refraction attenuation effects based on the empirical model are calculated for each frequency band, and are then summed log arithmetically to a single A-weighted overall excess refraction attenuation. Table 1 shows a comparison of the simulated refraction attenuation and reference results given in (3). The difference is not greater than 0.1 dB(A), which is caused by rounding error.

Table 1 – Comparison between Empirical Model Predicted Refraction Attenuation

Test cases	Wind shear (m/s/m)	Lapse rate (^{O}C/m)	Wind speed (m/s)	Our results dB(A)	Reference results dB(A)
1	0.032	-0.036	1.44	9.4	9.4
2	0.049	-0.030	1.66	9.4	9.4
3	0.056	-0.044	1.51	9.3	9.4
4	-0.017	-0.140	-1.92	9.8	9.9
5	-0.054	-0.137	-2.00	9.9	9.9

3.2 Traffic Noise Mapping

An in-house code based on CoRTN has been developed for noise prediction, with some validation examples presented in (12). It is combined with the atmospheric refraction model in this work for traffic noise mapping with consideration of meteorological effects. Figures 2 and 3 show the traffic noise mapping without / with meteorological effects. It is assumed that the road is a Category 1 one with input basic noise level as 77.2 dB(A). An obvious difference between the noise levels without and with meteorological effects is observed.

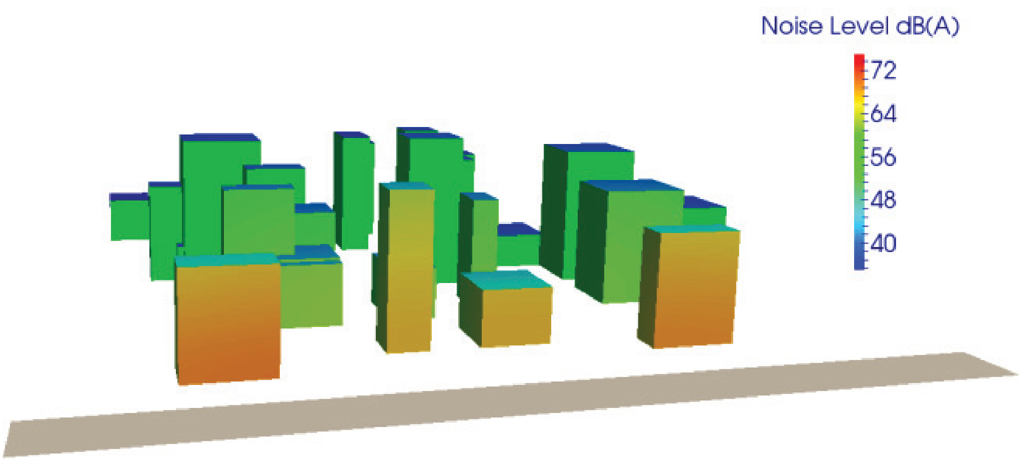


Figure 2 – Traffic noise level without meteorological effects

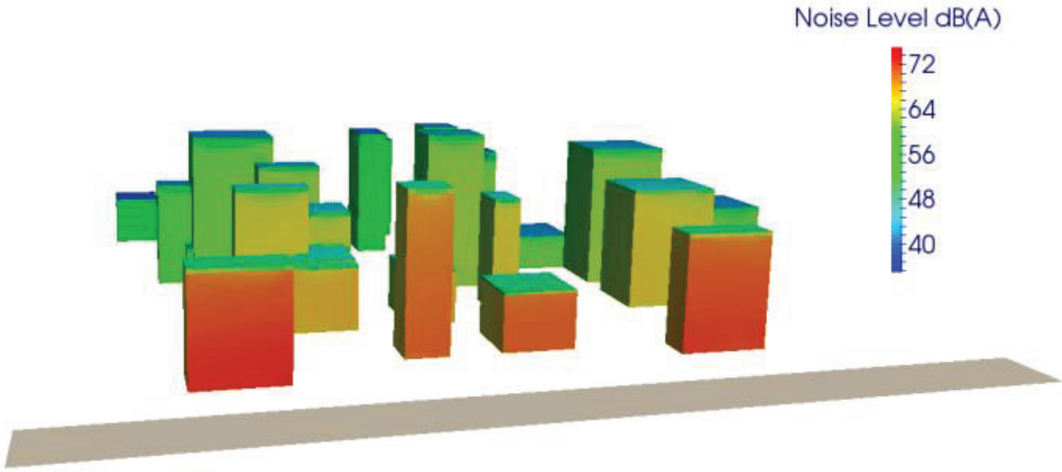


Figure 3 – Traffic noise level with meteorological effects

4. CONCLUSIONS

Atmospheric refraction dominates the effects on noise propagation caused by meteorological parameters. The incorporating of the atmospheric refraction model into the CoRTN model allows for a rough prediction of the traffic noise with meteorological effects.

ACKNOWLEDGEMENTS

This material is based on research/work supported by the Singapore Ministry of National Development and National Research Foundation under L2 NIC Award No. L2NICCFP1-2013-6.

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