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A general approach for extending the range of application of standard noise mapping methods

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Standard noise mapping software implements standard prediction methods. Such methods are often unable to predict the effects of complex or innovative noise reduction measures, and therefore unsuitable for local action planning or impact studies. On the other hand, advanced prediction schemes are considered too slow for practical use in noise mapping. In this paper we will present a new approach combining standard engineering noise prediction schemes with user-defined extensions. Extensions are used to predict level differences and/or additional insertion losses for the complex devices as compared to standard devices supported by the standards. The insertion losses can be estimated from experimental data, from analytical considerations or by means of numerical simulations. This approach can be used to implement such features as: barriers with cantilever, trenches with partial covering, interaction between train body and nearby barriers, reflections from complex walls, diffraction by screen tops, low barriers near traffic lanes, belts of trees with specific planting schemes, ground roughness elements… Extensions are implemented as independent software modules and therefore do not interfere with the standard methods. Disabling extensions allows calculation of noise maps according to legal requirements, enabling extensions allows assessment of noise levels at the local level, including the effects of innovative mitigations.

1 Introduction

Prediction software for environmental noise has been intensively used for more than 20 years now. Such software mainly implements standardized methods required by legal regulations as in the case of strategic noise mapping or the instruction of construction permits. In order to guarantee a maximum degree of reproducibility, standard methods use simplified input data based on classification, rather than on real, measured or predicted, acoustical performances.

In many situations, noise engineers would prefer to surpass the limitations of mandatory methods in order to predict local situations more realistically, i.e. take into account the real shapes and acoustical performances of planned mitigations more accurately. This is especially true when it comes to promoting and implementing innovative solutions. Such solutions may be rejected by decisions makers for the sole reason that they cannot be calculated by mandatory calculation schemes, which in turn are not adapted as long as innovation does not find its way into common practice.

In order to overcome these apparently contradicting requirements, a new way of implementing prediction schemes in software is proposed. This implementation uses a modular decomposition of the calculation scheme in which modules can be added or replaced at will. Additional user-defined modules, called “extensions”, make it easy to extend or adapt the possibilities of standard prediction schemes and to evaluate the performances of innovative solutions more accurately.

2 Modular software design

Over the past 10 years, many efforts have been made to establish more accurate and more powerful prediction schemes for engineering purposes[1,2,3]. The main tendency in this process is to replace so-called integrated methods by a modular approach, i.e. decoupling the emission part from the propagation part, through a common physically based source description. The propagation part can further be spit out into a geometrical part and an acoustical part. The acoustical calculations can be split into finer steps dealing separately with reflexions from walls and buildings, diffraction around vertical edges, diffraction over obstacles, reflexions from ground, meteorological effects...

Fig. 1 illustrates the decomposition of the prediction methods as implemented in CSTB’s prediction software. Conceptually, the calculation scheme is implemented as a pipelined architecture, i.e. a stack of independent processing units, one unit taking output from the previous one and providing input to the next.

Input to the stack is provided by the geometrical process in charge of constructing (purely geometrical) propagation paths[4]. A propagation path is the intersection of a horizontal plane with the boundaries of the three-dimensional geometrical model of the site. The propagation plane may be represented as a set of connected segments formed by the intersection of the plane with terrain, walls, buildings,... The propagation plane may change direction i.e. in case of reflections from walls or buildings or when diffracted around vertical edges.

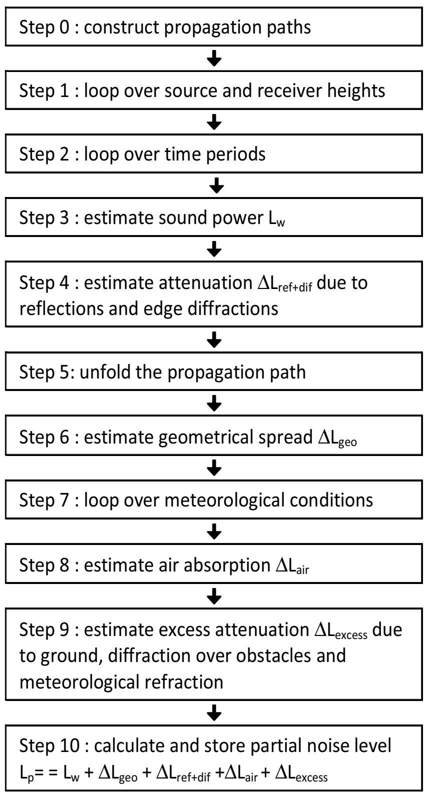

Figure 1: implementation of environmental noise prediction methods by means of a modular software design.

The propagation path may contain more than one source and more than one receiver (i.e. in case the emission model prescribes multiple equivalent sources at different heights). For efficiency reasons, the same geometrical path can be used to calculate noise levels for different periods whereas the sound power output of sources may vary over time.

Propagation effects in one period may be an average over different meteorological conditions.

Standard prediction schemes assume that the effects of reflections and diffractions from vertical obstacles, on one hand, and ground reflections and diffractions over obstacles under various meteorological conditions, on the other hand, can be separated. I.e. it is assumed that the latter can be calculated in the unfolded two-dimensional representation of the propagation plane. Albeit this principle is implicitly present in the textual description of all existing prediction methods, it takes the software designer some efforts to clearly identify this separation and to implement it in a modular way. In our software this is done as shown in steps 4 and 5 of Fig.1: attenuations due to vertical obstacles (i.e. changes in the direction of the horizontal projection of the path) are calculated first and then removed when unfolding the path. The Fermat principle assures that reflected and edge-diffracted ray paths from vertical obstacles become straight lines in the unfolded path.

Finally, the unfolded path is sent to the so-called point-to-point calculator as a set of connected segments in two dimensional coordinates (i.e. height versus distance along the path). The point-to-point module then estimates the effects of ground and diffraction over obstacles under various meteorological conditions. The modular design offers an efficient way to switch between available point-to-point prediction schemes: ISO 9613-2, NF S31-133 (a.k.a. NMPB-2008), Harmonoise...

3 Extensions and plug-in modules

Extensions are software modules that can be inserted anywhere in the processing chain. They must be prepared to accept input from the previous higher module and to provide output conforming to the interface of the next lower module in the chain. As a processing unit, an extension can take any of the following actions:

1. Return without calling the next module, thus cancelling further processing of the path.
2. Do nothing and pass on the path to the next module; this is useful if the extension has a limited range of applicability.
3. Modify the geometrical description of the path before transmitting it to the next module.
4. Modify the acoustical properties associated with parts of the propagation path.
5. Determine an extra level difference term ΔL_{ext} that will be added to the partial noise level determined in step 10.

In practice, extensions are implemented as options that end-users can enable or disable at will (usually from the graphical interface of the software) or as independent software modules placed in dynamically loadable libraries. In general, extensions can be configured by the end-user.

4 Elimination of paths

Most prediction methods put limits on propagation distances between the source and the receiver. Path finder algorithms can efficiently be programmed in order to limit the maximum length of the paths passed on to the noise calculations. Because of the modular decomposition, the maximum distance is a single value, independent of the source. In a complex noise mapping project however, many sources are present simultaneously and the unique limit value should therefore be set as a function of the strongest source present on the site. This is far from optimal.

In many situations, noise engineers have at least some prior knowledge about the radius of influence of dominant and secondary sources and this knowledge can be used to speed up the calculations by early elimination of non-relevant propagation paths. Although standards try to provide pragmatic rules with respect to such limits, it is obviously difficult to provide general rules applicable in all situations. Such rules should therefore not be hardcoded in software. Extensions provide an elegant solution to this problem.

Consider an additional module plugged in on top of the processing stack (i.e. before step 1). This module simply compares the length of the path to a source-specific limit value. This simple test will eliminate all non relevant paths in an early stage of the processing, thus saving valuable computation time.

The table below gives an example of parameters that might be used for eliminating paths depending only on equivalent hourly traffic. Elimination rules could be refined e.g. taking into account traffic speed and the % of heavy good vehicles, or even be based on some “quick and dirty” method for providing an initial estimate of the partial noise level associated with the path, e.g. by carrying out the calculations in dB(A) values or in a single frequency band.

Road type	Equivalent hourly traffic	Maximum distance
Motorway	> 2000 veh/h	1000m
Main road	> 1000 veh/h	500m
Secondary road	> 500 veh/h	200m
Local road	> 200 veh/h	100m

5 Sound power adaptors

One possibility offered by modular design is the mixing of source and propagation models from different standards. Because different methods use different ways to describe sources, the implementation is not straightforward. E.g. in the case of road vehicles, ISO and NMPB[4] methods use energy relations and predict attenuations relative to sound power radiated under hemispherical propagation conditions. On the other hand, Nord-2000 and Harmonoise[5] (and numerical methods in general) rely on sound pressure relations and refer to sound power radiated by point sources under free field conditions. It is a well known fact that the sound power output by a small source increases by 3 dB when it is placed immediately above a hard surface. This is consistent with the fact that, for a receiver close to the source, energy based methods predict a 3 dB level increase due to ground reflections, whereas pressure based methods predict a 6 dB increase of level compared to free field.

If the source is near but not on the ground, the effect of the hard ground surface can be estimated as[6]:

$$L_{W,hemi} = L_{W,free} + 10.log\left(1 + \frac{\sin(2kz_S)}{2kz_S}\right) \qquad (1)$$

This formula is easily implemented as an extension module and included in the processing chain between step 3 and 4. The table below shows the effect of mixing models for a typical motorway traffic (1000 LV/h at 100 km/h, 200 HGV/h at 90 km/h, reference road surface, aged 5 years). After introducing the sound power correction module, the results agree very well for the receiver positions nearest to the road. At larger distances, differences in the propagation model dominate over the source modelling.

As an extra feature, the extension offers the possibility to convert the original Harmonoise model (using 3 source heights) into a single equivalent source: the free field sound power output of the three sources is first converted to hemi-spherical sound power, summed and, if needed, converted back to a single point source at 30cm above the road surface. Once again, the results are close agreement with the others. It must be emphasised that such simplifications can reduce calculations time by more than 50%. Extensions make it possible to validate such simplifications without modifying the original code implementing the standard methods.

Emission model	Propagation model	Noise level in dB(A) versus distance			
		5m	10m	20m	50m
NMPB-2008[4]	ISO 9613-2	78.5	74.7	69.9	62.2
	NMPB-2008	78.7	74.9	71.2	62.8
	HARMONOISE	79.2	76.5	73.2	63.6
HARMONOISE[5] 3 source heights	ISO 9613-2	78.8	75.1	71.3	61.8
	NMPB-2008	79.0	75.3	71.3	61.8
	HARMONOISE	78.8	75.1	70.2	62.4
HARMONOISE 1 source at 30cm	ISO 9613-2	78.9	75.1	70.5	60.9
	NMPB-2008	79.1	75.3	71.1	61.4
	HARMONOISE	78.9	76.4	73.3	63.0

6 Equivalent source models

The NMPB-2008[2] standard indicates that multiple reflections between a train and a barrier near the track should be taken into account by means of image sources. As shown in Fig.2, higher order images of the source are less masked (and therefore less attenuated) by the barrier. Therefore, correct modelling of the screen-body effect should be considered when it comes to accurately predicting the efficiency of a barrier close to the track.

However, NMPB-2008 does not describe the full details for the implementation of this feature. It turns out difficult to integrate screen-body interaction in a geometrical path finder because the source line should be replaced by a vertical reflecting obstacle (or not) depending on the path under consideration. Moreover, because the algorithms used for the construction of propagation path differ significantly from one commercial software package to another, it is not feasible to provide a unique, consistent and reproducible approach without favouring one software implementation over another. It was therefore decided to consider an alternative solution based on equivalent source modelling.

Consider a propagation path connecting the original source S_0 to a receiver R. The path is diffracted over the top of a screen parallel to the track at a distance L_0 from the source (where L_0 is measured along the propagation path). In the unfolded propagation plane, multiple reflections between the car's body (assumed to be confounded with the source position) and the barrier, give way to successive image sources S_i, i = 1,...N at distances $L_i = (2.i+1).L_0$ from the barrier (see Fig.2). For this simplified configuration, the sound power of the equivalent source is given by:

$$L_{W,eq} = 10.log \sum_{i=0}^{N} 10^{\frac{L_W+\Delta L_i-\Delta L_0}{10}} \qquad (2)$$

where L_W is the sound power of the source in absence of the barrier, i.e. the output of the emission model for railway related sources, and ΔL_i is the attenuation term associated with the i-th image source. The attenuation term is estimated by means of a partial propagation model, taking into account:

- spherical divergence,
- diffraction by the top of the barrier,
- absorption on the inner side of the barrier,
- reflective properties of the car's body (expressed as a % of reflecting surfaces and stored as such in the database describing the units of rolling stock),
- the finite size of the reflecting surfaces (i.e. the retro-diffracting effect as described in NF S31-133).

One should note that this is a partial propagation model as ground reflections and meteorological effects are ignored at this stage. The equivalent sound power is used as input to the complete propagation model, thus preserving the modular design as outlined in section 2.

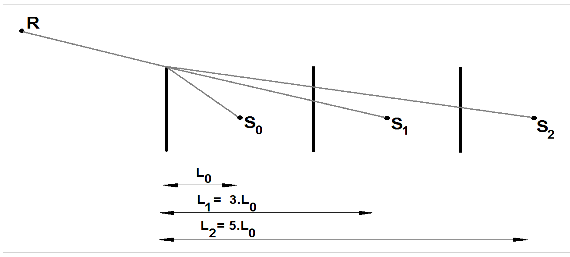

Figure 2: simplified geometry used to estimate the effect of multiple reflections between the train body and a barrier parallel to the track.

Because the equivalent sound power is a function of the source and receiver position, it must be re-evaluated for each propagation path. This is easily achieved by means of the extension idiom; i.e. by an additional module inserted between steps 3 and 4 of the standard processing chain.

The table below illustrates the effect of screen-body interaction on the efficiency of a barrier parallel to the railway track at 6m distance, 2m high relative to the head of the track. Images sources up to order 3 are taken into account. Ignoring the screen-body interaction the efficiency of the screen would be overestimated by more than 6 dB(A). Absorbing lining on the inner side of the screen suppresses the effects of multiple reflections and greatly improves the efficiency of the barrier.

By-pass level for a single TGV-R train	$L_{eq,A,Tp}$ versus distance			
	25m	50m	100m	200m
No barrier	90.3	86.0	80.7	74.7
Barrier, no interaction	80.8	75.6	70.7	64.4
Barrier, no absorption	86.4	82.3	77.9	71.9
Barrier, absorption $\alpha \approx 0.5$	83.8	79.3	74.9	68.7
Barrier, absorption $\alpha \approx 0.9$	81.5	75.6	70.7	64.4

Being an extension, the equivalent source model can be coupled with any emission model and/or any standard point-to-point module; its use and usefulness are therefore not limited to the original NMPB-2008 proposal. Moreover, not being hardcoded as part of the standard methods, the screen-body interaction module could easily be replaced with more advanced techniques, e.g. using extensive numerical calculations as described below.

7 Complex barriers

According to the ISO 9613-2 standard, any object may be assimilated with a barrier if it satisfies the enumerated requirements. However, its acoustical performances are estimated without distinction of shape or material.

The Hosanna[7] project aims to develop and promote innovative noise reduction techniques based on natural or recycled materials. The efficiency of these techniques is studies mainly by means of advanced numerical modelling. One of the objectives of the project is to provide an engineering model for the prediction of the efficiency of such devices in real life situations.

In the past, numerical experiments have been used to produce large data sets for non-standard barrier types[8]. From these data sets semi-empirical parametric formulae were derived and implemented as extensions in engineering software tools. This approach however has some pitfalls as it requires visual inspection and human interpretation of each specific case in order to identify the relevant input parameters and to select appropriate parametric forms for the estimated effects. Moreover, the approach is not without risks when the empirical formulas are extrapolated beyond the range covered by the numerical experiments.

In the Hosanna project, an alternative approach is being developed: instead of curve fitting, the extension will use automated interpolation from the pre-calculated dataset to estimate the effects of the innovative device along different propagation paths.

For the numerical simulations, the innovative device is placed in a simplified configuration representative for the foreseen range of applicability (see Fig.3). The receiver area is modelled as a 2-dim vertical grid on one side of the device; the sources are placed on a 3-dim. grid with heights taken from the representative emission model. Considering the symmetry of the problem, the y-coordinate of the receiver can be omitted as an input parameter and the calculations can be carried out efficiently using a 2-dim Boundary Element Method in combination with Duhamel's wave number transforms[9,10].

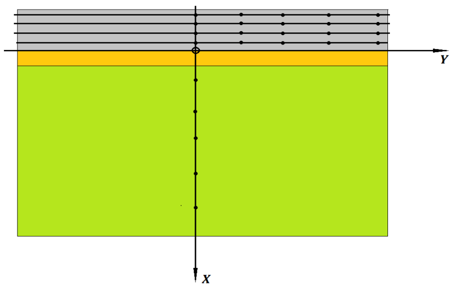

Figure 3: source and receiver grids used in BEM calculations, the barrier under study (yellow) is placed in between the source area (gray) and the receiver area (green)

The BEM calculations are used to estimate the insertion loss of the innovative (or complex) barrier as:

$$\Delta L_i = L_{p,i} - L_{p,REF,i} \tag{3}$$

where $L_{p,REF,i}$ refers to the sound levels without the barrier. On output, the calculated insertion losses are transformed to 1/3octave band and stored in tabular format together with the grid positions ($x_{S,i}$, $y_{S,i}$, $z_{S,i}$) and ($x_{R,i}$, $z_{R,i}$) of the source and the receiver respectively.

In order to estimate the efficiency of the innovative device in complex situations, a dedicated extension has been developed. This extension is used in conjunction with a classical ray-path algorithm and standard noise prediction schemes and is inserted next to step 5 of the common processing pipeline (i.e. after unfolding the path). It examines every propagation path in order to detect the presence of the innovative device as part of the path; paths not concerned by the device under consideration are passed on to the next step in the process without modification.

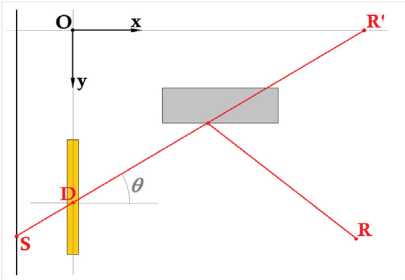

Figure 4: matching real-world coordinates to grid coordinates in case of a reflected propagation path

From the geometrical description of the path, the extension constructs a local coordinate system aligned with the barrier and matches the real-world coordinates to local coordinates used in the BEM grids. Because the extension operates on unfolded propagation paths in 2D, it handles indifferently direct, reflected and laterally diffracted paths. E.g. in the example shown in Fig.4, the geometry of the path is used to determine $d_S = |SD|$, $d_R = |DR'|$ and $cos(\theta)$, where θ is the angle (measured in the horizontal plane) between the propagation path and the normal to the barrier. The corresponding grid positions are calculated from:

$$\begin{aligned} x_S &= -d_S \cos(\theta) \\ y_S &= (d_S + d_R)\sin(\theta) \\ x_R &= d_R \cos(\theta) \end{aligned} \tag{4}$$

To interpolate the insertion loss of the barrier at the specified position, we use the modified Shepard's method[11] over the 5-dimensional vector space $\boldsymbol{x} \equiv (x_S, y_S, z_S, x_R, z_R)$. The interpolating function is defined as:

$$f(x) = \frac{\sum_{i\in K} W_i(x) Q_i(x)}{\sum_{i\in K} W_i(x)} \tag{5}$$

where the set K is limited to the N_W nearest neighbours of x. The weighting functions are defined by:

$$W_i(x) = \left(\frac{R_X - \|x - x_i\|}{R_X \|x - x_i\|}\right)^2 \tag{6}$$

with:

$$R_X = \max_{i\in K} \|x - x_i\| \tag{7}$$

The nodal functions $Q_i(x)$ are linear forms obtained from weighted least squares fitting on the sets K_i containing the N_Q nearest neighbours of each control point x_i under the constraint $Q_i(x_i)=y_i$.

As the weighting function vanishes outside a ball of radius R_X centred at $\boldsymbol{x}$, the evaluation of eq.(5) requires little computation effort. The search for the N-th nearest neighbours has *O(log(N)* complexity and is implemented efficiently by means of a kd-tree data structure.

The automated interpolation has been validated for the well-known case of a single point source behind a 4m high straight barrier. For our initial tests, the parameters of the interpolation method were set to N_W = 32, N_Q = 6. The results of the test are shown in Fig.5. It may be noted that the BEM results are systematically lower than those predicted by the NMB-2008 method, which can be explained by corrections to the source term (as explained in section 5), not included in this test. The agreement between the mixed approach (using insertion losses estimated by means of BEM calculations) and the analytical formulation from the NMPB-2008 standard is excellent with deviations less than 0.5 dB(A).

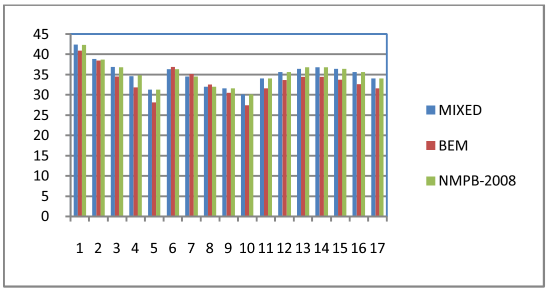

Figure 5: validation of automated interpolation technique for a single point source and a straight barrier 4m high.

Because the “reference” is a configuration without the barrier, the extension must remove the barrier from the geometrical description of the propagation path before sending the path to the standard point-to-point calculation schemes.

Alternatively, one might use an equivalent (straight, flat, hard) barrier as the reference configuration. In that case, the BEM calculations are used to estimate the difference in insertion loss between the classical barrier and the innovative (complex) device. This approach would have the advantage that it does not interfere with the estimation of ground effects on source and receiver side as implemented in the NMPB-2008 or Harmonoise methods and therefore allows for extrapolating of the pre-calculated results to situations with different ground types.

The Hosanna project will continue to develop and validate heuristic modelling techniques combining intensive numerical calculations with fast engineering models based on efficient construction of propagation paths. The principles outlined in this section will be applied to different types of innovative noise reduction devices such as low barriers, mounds, ground roughness elements, trees, shrubs and bushes, advanced road surface technologies... or any combination of these.

Directional reflections coefficients for complex walls may also be considered, e.g. in the framework of the Quiesst project.

Conclusion

In this paper, extensions were introduced as a flexible and efficient means to add optional features to standard noise predictions schemes without breaking existing code. It was shown how extensions can be used to reduce computation times in large noise mapping projects, to check simplifications and adaptations of existing model, to predict more accurately the effects of innovative mitigations...

As extensions can be enabled or disabled at will, they do not interfere with existing code implementing mandatory methods used in national or international regulations.

Object oriented modelling has revolutionised the way software is designed and developed. It would make life easier for software engineers if standard prediction schemes were drafted in a more software-friendly way, taking full advantage of the paradigms and idioms of object oriented thinking.

Acknowledgments

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