Influence of railway track topography on acoustic propagation of railway noise: experimental setup and comparison with numerical calculations

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Journées GdR VISIBLE

Outdoor sound propagation

- boundary effects
- atmospheric effects

Transportation noise

- broadband noise
- source in motion
- propagation distances up to 5 km

Numerical simulation needed to take into account all these effects

Possible methods:

- parabolic equation,
- ...

Acoustic measurement along a high speed track

TGV travelling at a speed of 320 km/h

Time domain solution of the linearized Euler equations

- **Atmospheric effects** taken into account (mean wind and mean temperature profile)
- **Time-domain impedance boundary condition (TDBC):**
  - has been studied in the CAA community to model the impedance of lining materials: Tam & Auriault (1996), Özyörük & Long (1997), Jung & Fu (2001), Rienstra (AIAA Paper 2006-2686), Reymen *et al.* (2007)
  - becomes an important issue in outdoor sound propagation studies: Salomons *et al.* (2002), Wilson *et al.* (2006), Ostashev *et al.* (2007)
  - TDBC proposed by Cotté *et al.* (AIAA J., **47(10)**, 2009)
- Numerical configurations over an impedance flat ground in a stratified atmosphere (Dragna *et al.*, AIAA J., 2011)

GOAL: Validation of the numerical model with experimental results obtained on a railway track site

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Context

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1 Outdoor sound propagation model

2 Experimental setup

3 Comparison with numerical calculations

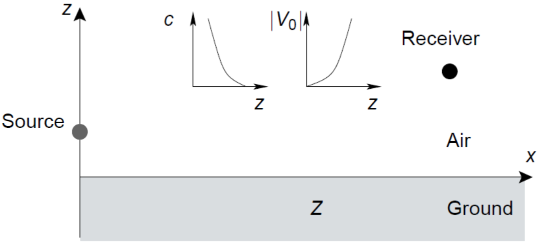
4 Conclusions

Outdoor sound propagation model

Time domain solution of the linearized Euler equations:

$$\frac{\partial p}{\partial t} + \mathbf{V_0}.\nabla p + \rho_0 c^2 \nabla.\mathbf{v} = \rho_0 c^2 Q,$$

$$\rho_0 \frac{\partial \mathbf{v}}{\partial t} + \rho_0(\mathbf{V_0}.\nabla)\mathbf{v} + \rho_0(\mathbf{v}.\nabla)\mathbf{V_0} + \nabla p = \mathbf{R}.$$



Scheme of the problem

Time domain solution of the linearized Euler equations under the conservative form:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \frac{\partial \mathbf{G}}{\partial z} + \mathbf{H} = \mathbf{S},$$

where the unknow vector $\mathbf{U} = [p,\ \rho_0 v_x,\ \rho_0 v_y,\ \rho_0 v_z]^T$ and the fluxes are given by:

$$\mathbf{E} = \begin{pmatrix} V_{0x} p + \rho_0 c^2 v_x \\ V_{0x} \rho_0 v_x + p \\ V_{0x} \rho_0 v_y \\ V_{0x} \rho_0 v_z \end{pmatrix}, \mathbf{F} = \begin{pmatrix} V_{0y} p + \rho_0 c^2 v_y \\ V_{0y} \rho_0 v_x \\ V_{0y} \rho_0 v_y + p \\ V_{0y} \rho_0 v_z \end{pmatrix}, \mathbf{G} = \begin{pmatrix} V_{0z} p + \rho_0 c^2 v_z \\ V_{0z} \rho_0 v_x \\ V_{0z} \rho_0 v_y \\ V_{0z} \rho_0 v_z + p \end{pmatrix},$$

$$\mathbf{H} = \begin{pmatrix} 0 \\ \rho_0 \mathbf{v}.\nabla V_{0y} \\ \rho_0 \mathbf{v}.\nabla V_{0x} \\ \rho_0 \mathbf{v}.\nabla V_{0z} \end{pmatrix}, \mathbf{S} = \begin{pmatrix} \rho_0 c^2 Q \\ R_x \\ R_y \\ R_z \end{pmatrix}.$$

Time domain solution of the linearized Euler equations under the conservative form:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \frac{\partial \mathbf{G}}{\partial z} + \mathbf{H} = \mathbf{S},$$

Numerical techniques:

- Spatial derivatives: finite difference schemes (Bogey & Bailly, JCP, 2004)
- Time integration: optimized six-stage Runge-Kutta scheme (Bogey & Bailly, JCP, 2004)
- Spatial filtering (Bogey *et al.*, JCP, 2009)

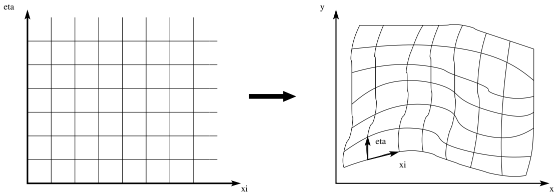
Non-reflecting boundary conditions:

- based on far-field asymptotic expression of the linearized Euler equations (Tam & Dong, JCA, 1996)

Topography

Ideas of the community of computational aeroacoustics (Marsden, JCA, 2005)

- Mesh



- Linearized Euler equations under conservative form for the cartesian case

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial z} + \mathbf{H} = \mathbf{S},$$

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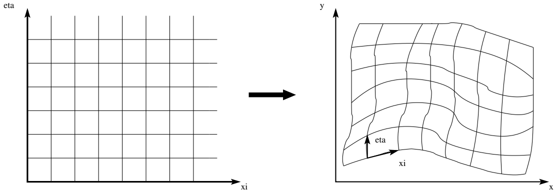

- Linearized Euler equations under conservative form for the curvilinear case

$$\frac{\partial \mathbf{U}^*}{\partial t} + \frac{\partial \mathbf{E}^*}{\partial \xi} + \frac{\partial \mathbf{F}^*}{\partial \eta} + \mathbf{H}^* = \mathbf{S}^*,$$

$$\mathbf{U}^* = \frac{\mathbf{U}}{J}, \quad \mathbf{E}^* = \frac{\xi_x \mathbf{E} + \xi_z \mathbf{F}}{J}, \quad \mathbf{F}^* = \frac{\eta_x \mathbf{E} + \eta_z \mathbf{F}}{J}, \quad \mathbf{H}^* = \frac{\mathbf{H}}{J} \text{ and } \mathbf{S}^* = \frac{\mathbf{S}}{J}.$$

Time-domain boundary condition

Impedance boundary condition

frequency-domain boundary condition		time-domain boundary condition
$P(\omega) = Z(\omega) V_N(\omega)$	$\Longrightarrow$	$p(t) = \int_{-\infty}^{+\infty} v_N(t - t') z(t') dt'$

Translation into the time domain can be done if the impedance model is **physically possible**:

- **causal** model: $Z(\omega)$ is analytic and non-zero in $\mathrm{Im}(\omega) > 0$
- **real** model: $Z^*(\omega) = Z(-\omega)$
- **passive** model: $Re[Z(\omega)] \geq 0$

For instance, Delany & Bazley impedance model is not real

Time-domain impedance boundary condition

1. approximate $Z(\omega)$ by a rational function
(Fung & Ju, 2001; Reymen *et al.*, 2007; Cotte *et al.*, 2009)

$$Z(\omega) \approx \sum_{k=1}^{S} \frac{A_k}{\lambda_k - j\omega} + Z_\infty, \quad \text{Re}[\lambda_k] \geq 0$$

Z_∞ can be set to zero but has to be equal to $Z_\infty = \lim_{\omega \to +\infty} Z(\omega)$ for large broadband calculations

2. Recursive convolution method (PCRC method) for real poles λ_k
(Luebbers & Hunsberger, 1992)

$$p^{(n)} = \sum_{k=1}^{S} A_k \phi_k^{(n)}$$

$$\phi_k^{(n)} = v_N^{(n)} \frac{1 - e^{-\lambda_k \Delta t}}{\lambda_k} + \phi_k^{(n-1)} e^{-\lambda_k \Delta t}$$

with $p^{(n)} = p(n\Delta t)$ and $v_N^{(n)} = v_N(n\Delta t)$

The velocity normal to the ground is given by:

$$v_N = \frac{1}{|\nabla \eta|} \nabla \eta . \mathbf{v}$$

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Experimental setup

Measurements carried out in La Veuve (near Reims) in May 2010:

- topographical account
- in-situ ground impedance measurements
- meteorogical measurements
- acoustical measurements:

  5 receivers located at 3 m, 7.5 m, 25 m, 100 m, 200m and 300 m from the centerline of the track

  blank pistol shots: 3 shots

Comparisons realized with 2D calculations

Measurement site

Topographical account

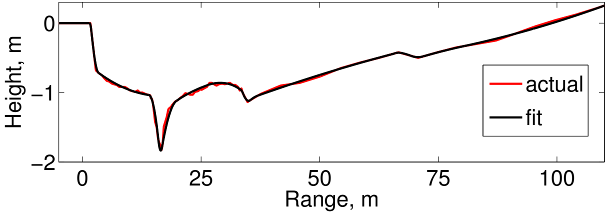
Measurement realized along the propagation line

- $\Delta x \simeq 0.1$ m for distances lower than 30 m
- $\Delta x \simeq 4$ m for distances greater than 30 m

Smooth profile terrain obtained with a quadratic spline approximation

Implementation with the coordinate transform:

$$\begin{cases} x = \xi, \\ z = \eta + H(\xi), \end{cases}$$

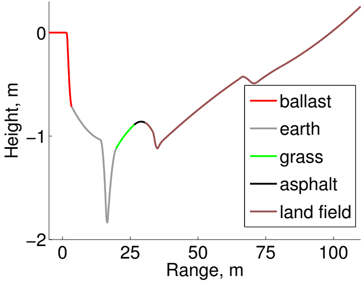


Impedance measurements

Five different ground surfaces

- ballast bed
- earth
- grassy ground
- asphalt ground
- land field

In-situ measurements realized by IFSTTAR



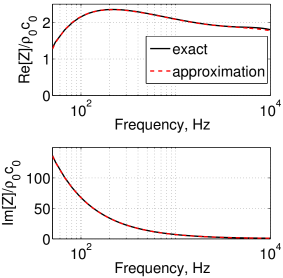
Ground surfaces

Impedance modelling

"Classical" grounds: one-parameter Miki impedance model of a rigidly backed layer

- effective flow resistivity σ_e
- effective thickness e

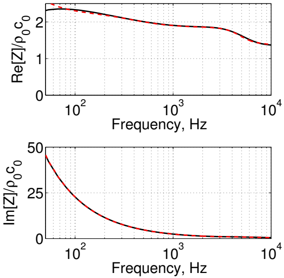
Earth:



$\sigma_e = 420$ kPa.s.m^{-2}

$e = 0.006$ m

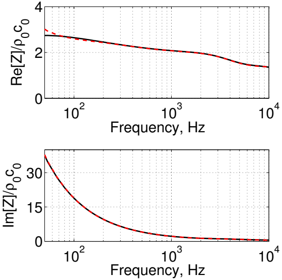
Grassy ground:



$\sigma_e = 140$ kPa.s.m^{-2}

$e = 0.018$ m

Land field:



$\sigma_e = 130$ kPa.s.m^{-2}

$e = 0.022$ m

Asphalt ground: perfectly reflecting surface

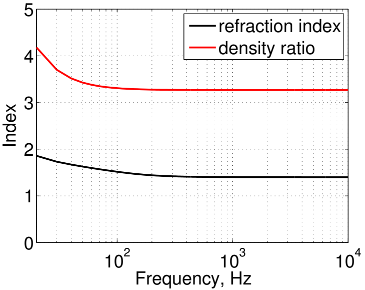
Impedance modelling

Ballast ground:

Porous medium

Hamet & Berengier impedance model:

- porosity $\Omega = 0.6$
- tortosity $q = 1.4$
- flow resistivity $\sigma_0 = 0.4$ kPa.s.m^{-2}
- thickness $e = 0.68$ m



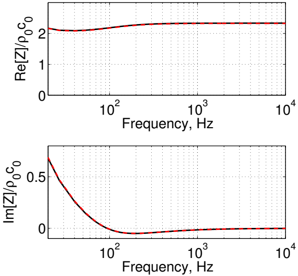
Index of refraction and density ratio versus frequency

Refraction index close to one $\rightarrow$ Local reaction is a poor assumption

Ballast ground:

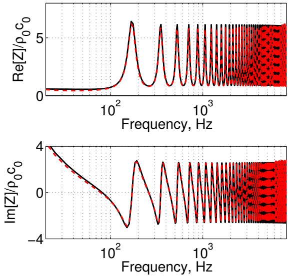
Two simulations with different modelling for the ballast bed:

Semi-infinite ground:



$e = \infty$

Effect of thickness:



$e = 0.68$ m

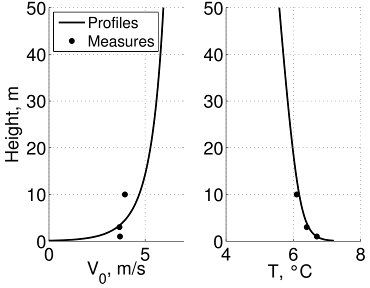
Meteorogical measurements

Meteorological mast located at 125 m from the track:

- humidity
- atmospheric pressure
- temperature at 1 m, 3 m and 10 m
- wind amplitude and direction at 1 m, 3 m and 10 m

Monin and Obukhov similarity theory to determine the profiles

Obukhov length: $L \simeq 150$ m characteristic of an unstable atmosphere



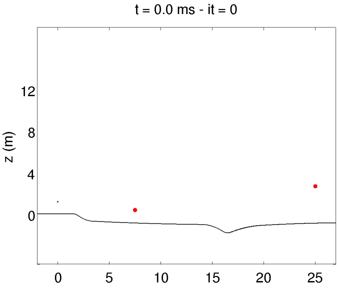
Numerical calculations

First numerical calculation: 2D geometry with propagation distances up to 25 m

Spatial mesh size equal to $\Delta x 0.5$ cm $\rightarrow$ up to $\sim$ 10 000 Hz

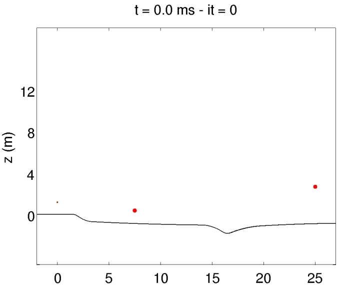
CFL number = $c_0 \Delta t / \Delta x$ set to 0.4

Source: Gaussian pulse



Ballast bed with finite thickness

pause *play*

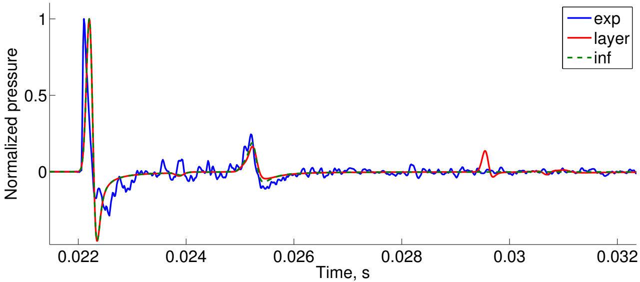


Ballast as a semi-infinite ground

pause *play*

Comparison in the time-domain

Receiver at 7.5 m



First arrival: $t \simeq 22$ ms direct wave

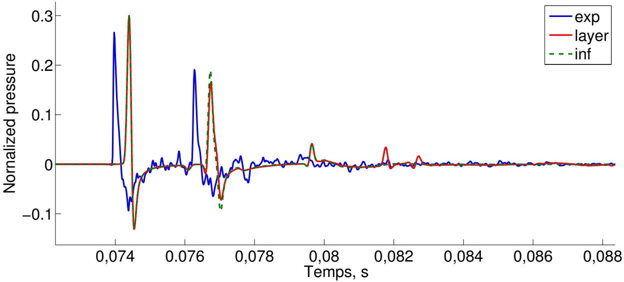
Second arrival: $t \simeq 24$ ms wave reflected on the ballast bed

Third arrival: $t \simeq 25$ ms wave reflected on the ground

Others arrivals predicted if the thickness of the ballast bed is taken into account

Comparison in the time-domain

Receiver at 25 m



First arrival: $t \simeq 74$ ms direct wave

Second arrival: $t \simeq 78$ ms reflection on the ballast bed

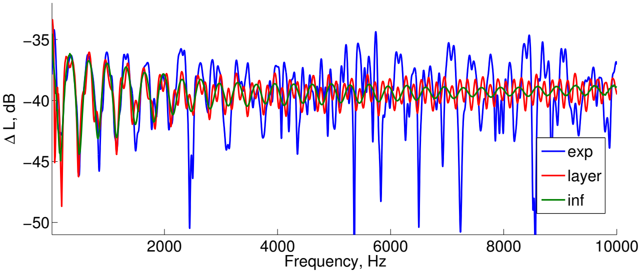
Third arrival: $t \simeq 79$ ms reflection on the ground

Fourth arrival: $t \simeq 84$ ms reflection and diffraction at the gap

Others arrivals predicted if the thickness of the ballast bed is taken into account

Comparison in the frequency-domain

Receiver at 7.5 m

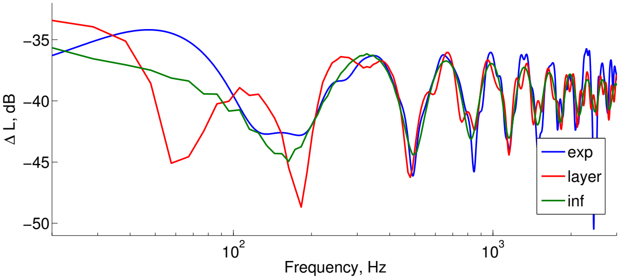


Sound level relative to the free field

Good agreement for frequencies lower than 3000 Hz

Comparison in the frequency-domain

Receiver at 7.5 m



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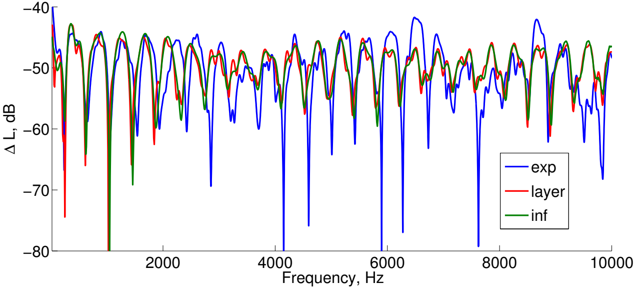

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Better agreement if the ballast is assumed as a semi-infinite ground

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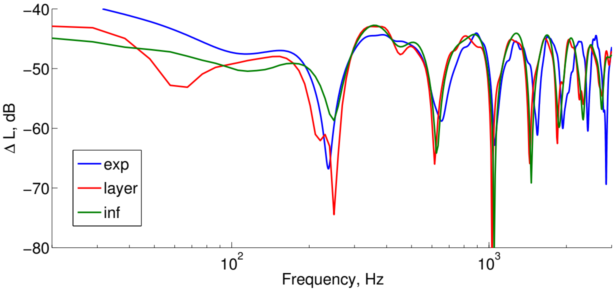

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Conclusions:

Numerical model for outdoor sound propagation

Most of phenomena are taken into account

Limitation for locally reacting ground

Good agreement obatined with experimental results for receivers at close distances

Perspectives:

3D calculations are in progress

Coupling between near-field and far-field calculations

Sources in motion

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