Inverse estimation of the properties of porous ground surfaces from in-situ sound absorption measurements

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Summary

- A method is proposed for extracting a set of properties of porous ground surfaces from acoustic impedance measurements performed in situ.
- The ground is modelled as a layer of rigid-frame porous material using a model by Hamet and Bérengier, which consists of four parameters: the porosity, the tortuosity, the flow resistivity and the thickness of the material layer.
- The parameters are estimated as the underlying set of values which provide a best fit of model predictions onto experimental data.
- The model fitting process is formulated as an optimisation problem and the parameter search is automated using an optimisation algorithm.

Model

Porous ground surfaces can be modelled as rigid porous solids and approximated by an equivalent fluid where a single compressional wave exists.

Phenomenological model (Hamet and Bérengier [1])

$$\begin{cases} \text{Specific impedance: } Z_0(\omega) = \dfrac{\rho c}{\phi}\dfrac{A(\omega)}{B(\omega)} \\ \text{Wavenumber: } k(\omega) = \dfrac{\omega}{c}A(\omega)B(\omega) \end{cases}$$

$$A(\omega) = \sqrt{K\left(1 - i\frac{\omega_\mu}{\omega}\right)} \qquad B(\omega) = \sqrt{\gamma\left(1 - \frac{1-1/\gamma}{1-i\omega_\theta/\omega}\right)}$$

$\omega_\mu = \dfrac{\sigma\phi}{\rho K}$ and $\omega_\theta = \dfrac{\sigma}{\rho \mathrm{Pr}}$: viscous and thermal characteristic frequencies

Model parameters

- ϕ = porosity
- K = shape factor
- σ = flow resistivity
- h = thickness of the material layer

Properties of air
$\rho = 1.2\,\mathrm{kg{\cdot}m^{-3}}$ (density)
$c = 344\,\mathrm{m{\cdot}s^{-1}}$ (speed of sound)
$\gamma = 1.4$ (ratio of specific heats)
$\mathrm{Pr} = 0.71$ (Prandtl number)

Normal impedance of the ground

- Ground material backed by a rigid wall: $Z(\omega) = -iZ_0(\omega)\cot(k(\omega)h)$
- Ground material backed by a soft wall: $Z(\omega) = iZ_0(\omega)\tan(k(\omega)h)$
- Infinite material thickness: $Z(\omega) = Z_0(\omega)$

Reflection coefficient: $R(\omega) = \dfrac{Z(\omega) - \rho c}{Z(\omega) + \rho c}$

Sound absorption coefficient: $\alpha(\omega) = 1 - |R(\omega)|^2$

[1] J.F. Hamet and M. Bérengier. Acoustical characteristics of porous pavements: A new phenomenological model. In *Internoise 93*, pages 641–646, Leuven, 1993.

[2] J. Cuenca, C. Van der Kelen, and P. Göransson. A general methodology for inverse estimation of the elastic and anelastic properties of anisotropic open-cell porous materials—with application to a melamine foam. *J. Appl. Phys.*, 115(8):–, 2014.

[3] L. De Ryck, J. Cuenca, and K. Menino. Innovative estimation methods of in-situ sound absorption : Beyond the iso standards. In *SAPEM 2014*, Stockholm, 2014.

[4] K. Svanberg. A class of globally convergent optimization methods based on conservative convex separable approximations. *SIAM Journal on Optimization*, 12(2):555, 2002.

Inverse estimation method

The properties (ϕ, K, σ, h) of a porous ground surface are obtained as the set providing the best fit of the model onto on-site measurements of the sound absorption coefficient, following the methodology in Ref. [2]. The measurements may be performed using a standard two-microphone impedance tube, or more advanced methods [3].

Model curve-fitting formulated as an optimisation problem

$$\min f_{\mathrm{obj}}(\mathbf{x}) = 1 + \sum_n |\alpha(\mathbf{x}, \omega_n) - \alpha_0(\omega_n)|^2$$

- $\alpha_0(\omega_n)$: measured absorption coefficient
- $\alpha(\mathbf{x}, \omega_n)$: absorption coefficient predicted by the model at frequency ω_n for a given set of parameters $\mathbf{x} = \{\phi, K, \sigma, h\}$

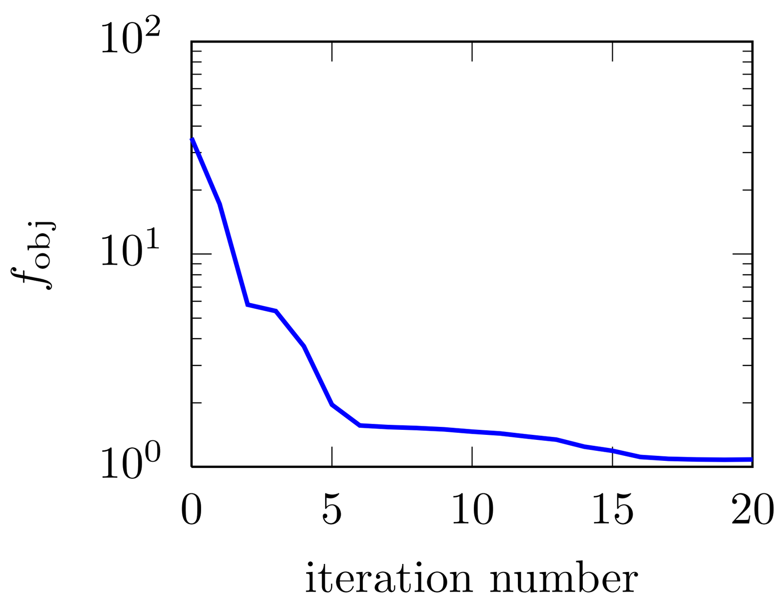
The problem is solved using an optimisation algorithm [4].

Validation on a rigid-backed gravel sample

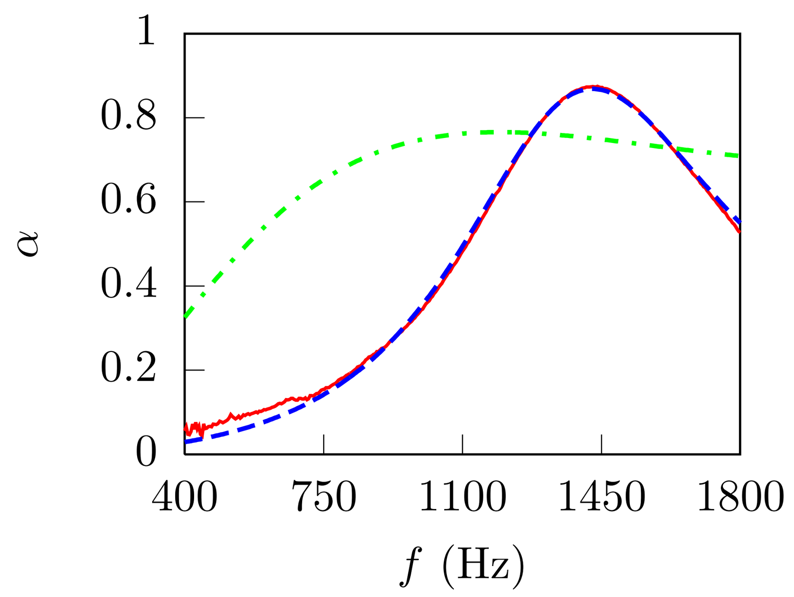
The method is here validated on a 41 mm-thick sample of rigid-backed gravel.

(a) Gravel sample

(b) Impedance tube



(c) Evolution of the objective function



(d) Sound absorption coefficient (full line: experiment; dashed-dotted line: arbitrary initial guess; dashed line: fitted model)

Figure 1: Rigid-backed gravel sample and curve fit.

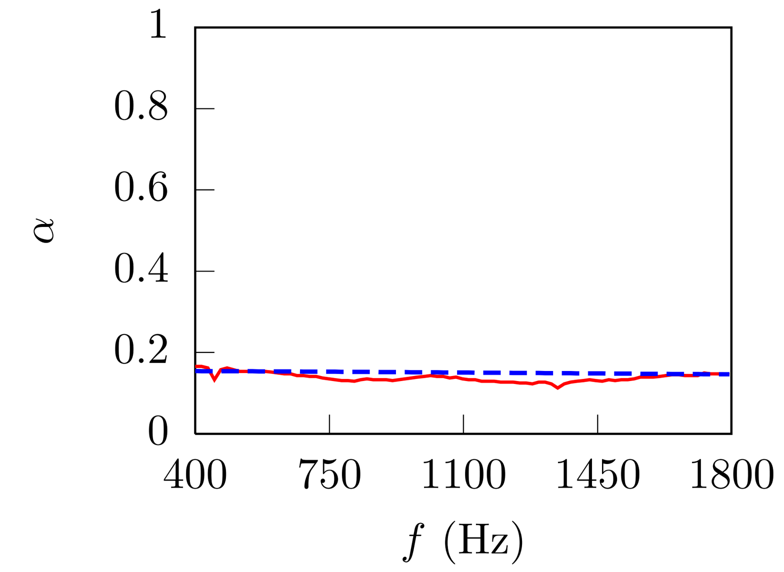
Parameter	Symbol	Estimated value
Porosity	ϕ	0.155
Shape factor	K	1.54
Flow resistivity	σ	$36824\,\mathrm{N{\cdot}s{\cdot}m^{-4}}$
Thickness	h	0.0414 m

Table 1: Estimated parameters for a rigid-backed sample of gravel.

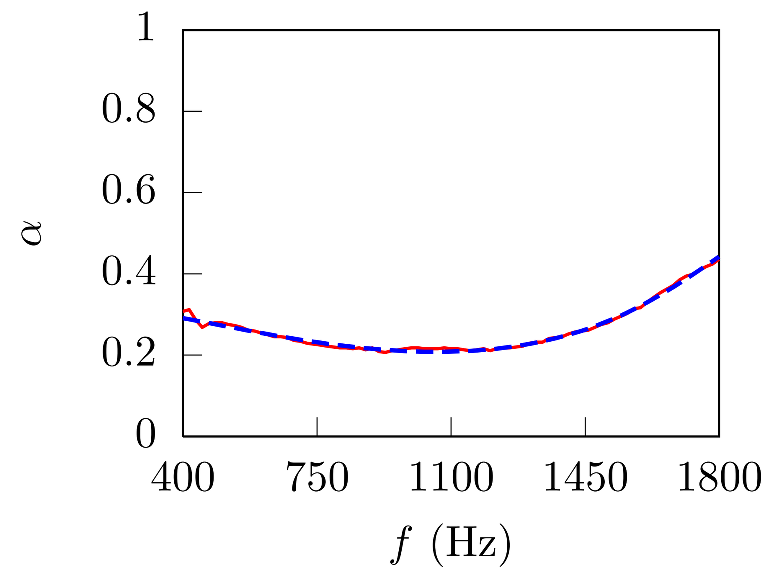
Application to in-situ ground measurements

The method is applied to the estimation of the properties of outdoor ground surfaces. On-site measurements of the sound absorption coefficient are performed on grass, gravel and asphalt.

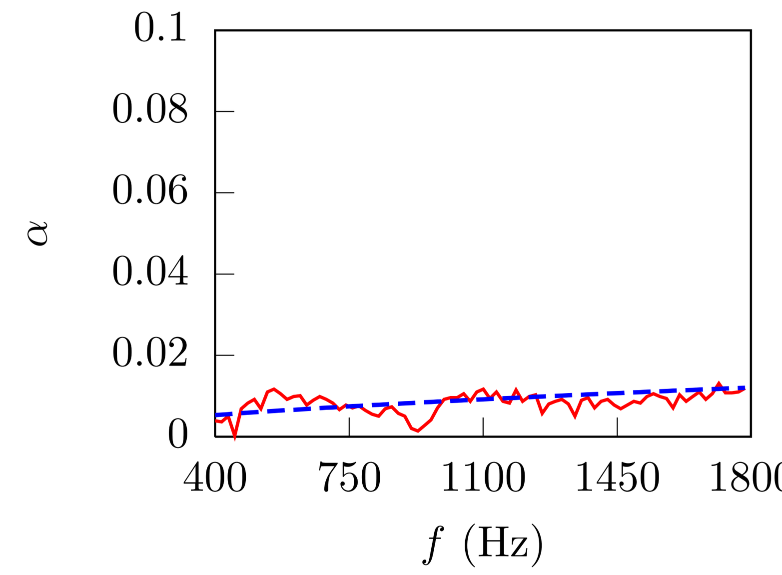
(a) Impedance tube



(b) Grass



(c) Gravel



(d) Asphalt

Figure 2: Sound absorption coefficient for different ground surfaces. (Same key as Fig. 1(d).)

Parameter	Symbol	Estimated value			unit
		Grass	Gravel	Asphalt	
Porosity	ϕ	0.1055	0.317	0.015	-
Shape factor	K	8.79	7.89	6.47	-
Flow resistivity	σ	10982	167503	19407172	$\mathrm{N{\cdot}s{\cdot}m^{-4}}$
Thickness	h	-	0.024	-	m
Boundary condition		∞	F	∞	

Table 2: Estimated parameters for grass, gravel and asphalt.

Observations and conclusions

- A simple methodology has been developed for measuring a set of properties of the upper layer of a ground surface.
- The method is applicable to a homogeneous porous ground layer under the rigid-frame approximation.
- The simplified model does not capture the full complexity of the ground, such as its stratified nature or its inhomogeneity. In particular, a more detailed description of the boundary conditions at the interface between the tested layer and the soil underneath is required.