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# Multilayer modelling of thermoacoustic sound generation for carbon based nanomaterial thermophone

Guiraud Pierre<sup>1,2,3,4</sup>, Giordano Stefano<sup>1</sup>, Bou-Matar Olivier<sup>1</sup>, Djamilia Hourlier<sup>1</sup>, Lardat Raphael<sup>2</sup>, Coquet Philippe<sup>1,3</sup>, Pernod Philippe<sup>1</sup>

<sup>1</sup> IEMN (Institut d'électronique de microélectronique et de nanotechnologie) UMR CNRS 8520, Villeneuve d'Ascq

<sup>2</sup> Thales Underwater System France, Sophia Antipolis, 525 Route des Dolines, F-06560 Valbonne

<sup>3</sup> CINTRA UMI 3288 CNRS/NTU/Thales, Research Techno Plaza, 50 Nanyang Drive 637553, Singapore

<sup>4</sup> DGA (Direction Générale des Armées) France



## Introduction

The thermoacoustic effect is based on applying an **alternative current** to a material with a **high thermal conductivity** and a **low thermal capacity**. The heat profile of the material follows the current profile and the compression dilatation of the air on the surface of the material due to the fluctuating temperature generates an acoustic wave whose frequency is proportional to the input frequency of the current. Since no resonating part are involved in the process the generation is **wideband**.

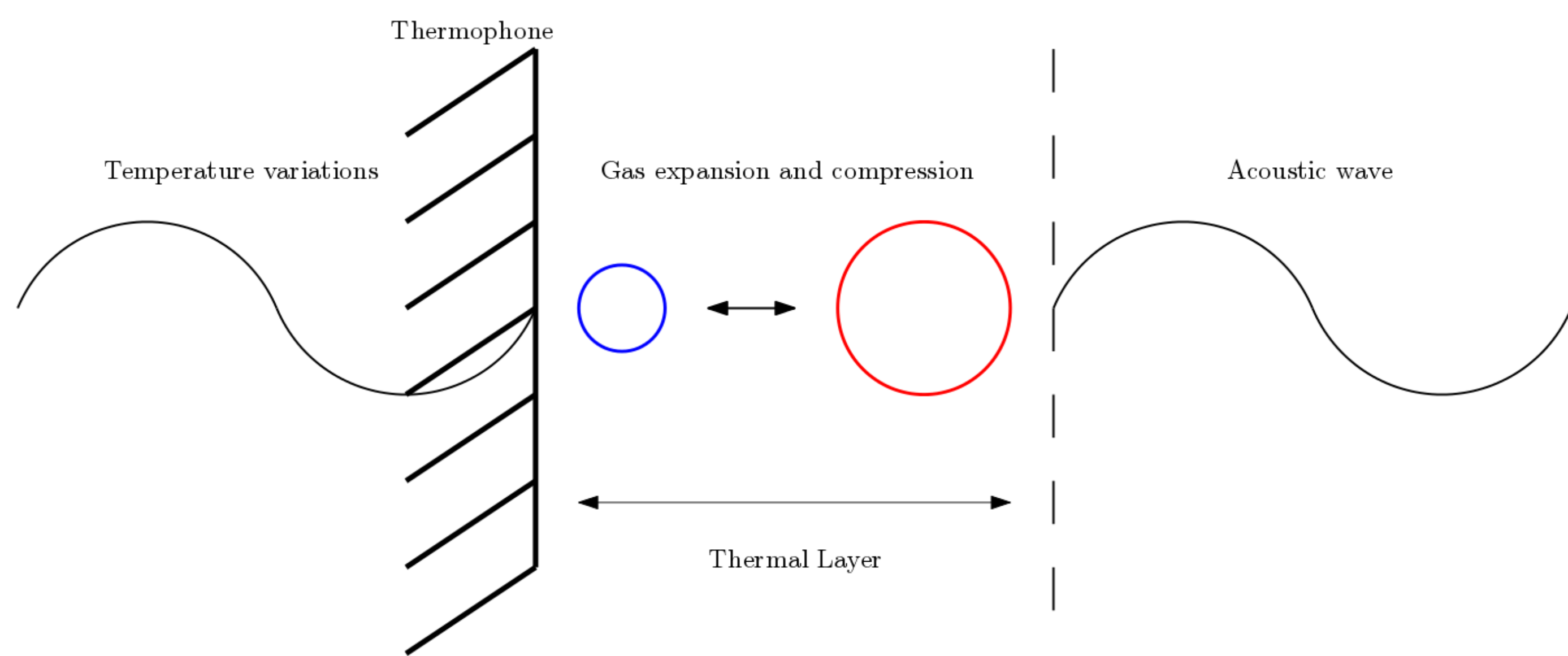
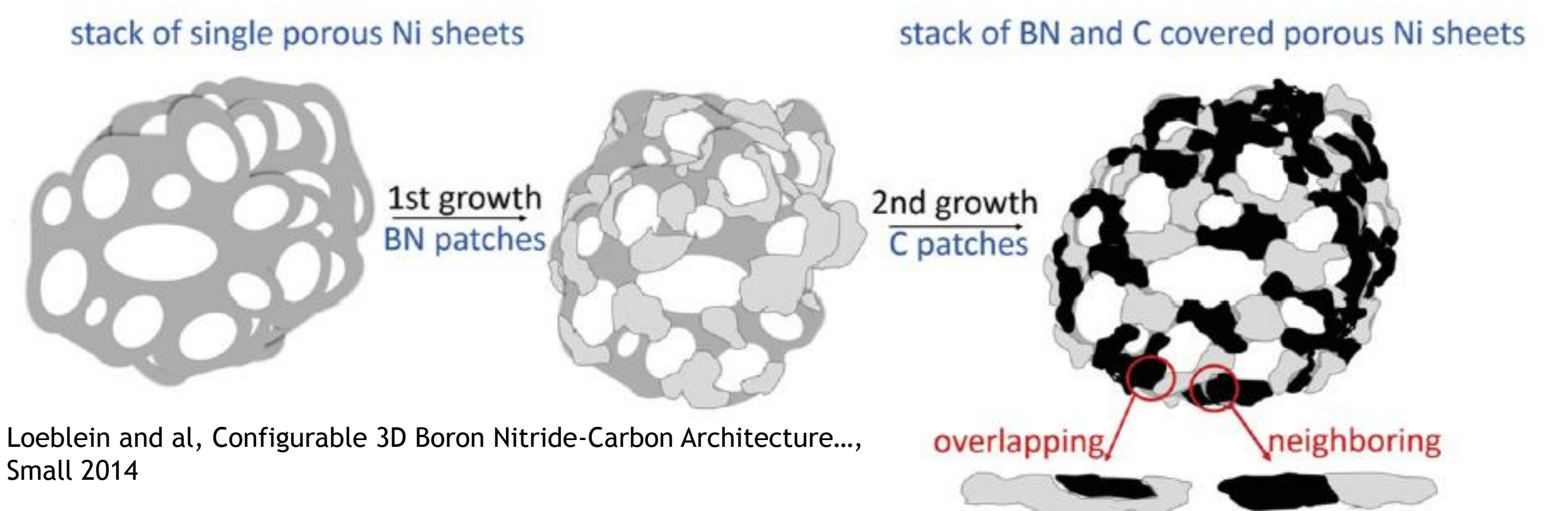


Fig.1: Schematic representation of the thermophone sound generation

## Thermophone design



Loeblin and al, Configurable 3D Boron Nitride-Carbon Architecture... Small 2014

Fig.2: Chemical Vapor Deposition method used for nanomaterial fabrication

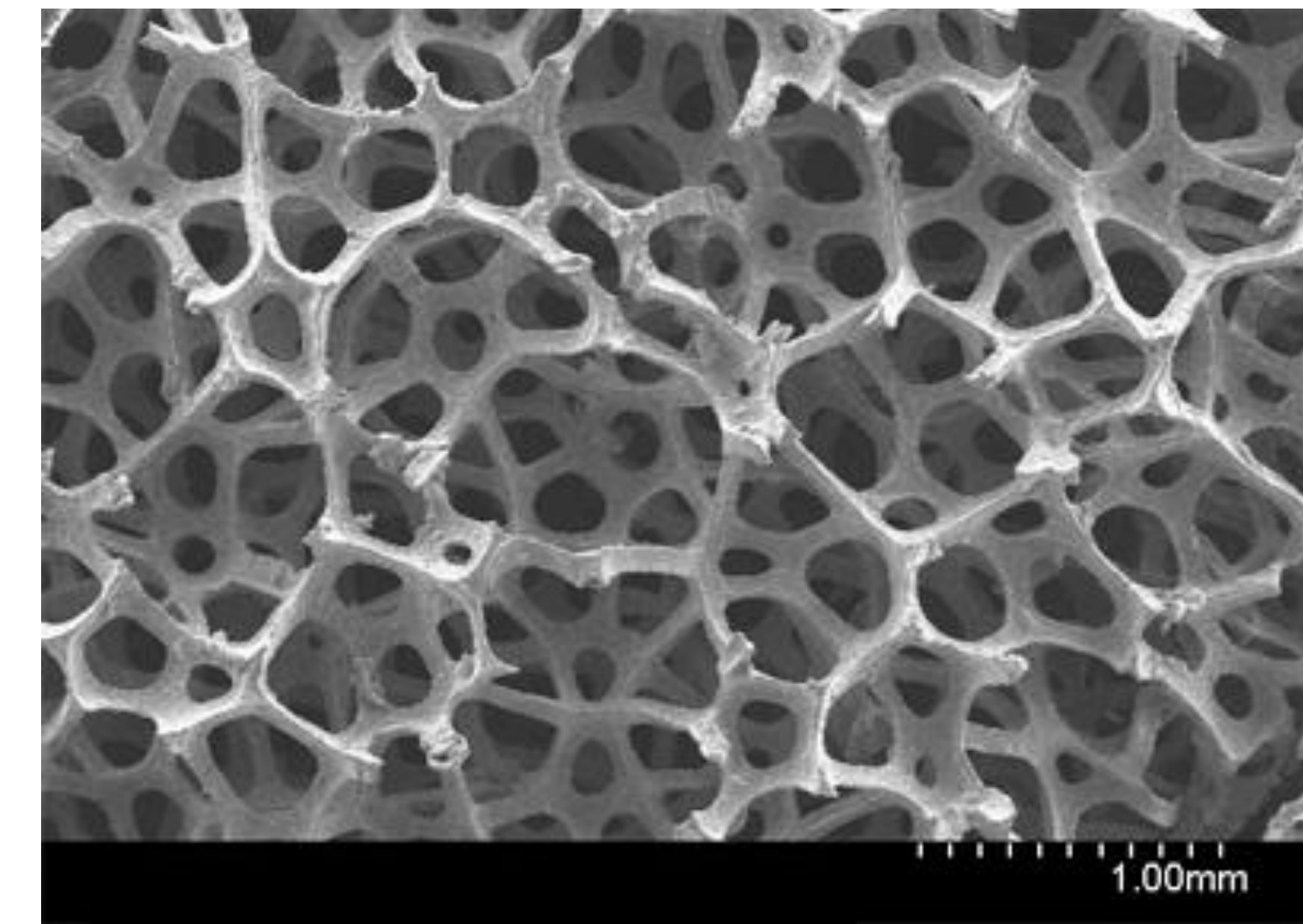


Image from https://graphene-supermarket.com/3D-Graphene-Foams

Fig.2: 3D Graphene foam image

## Theory and Multi-Layers Modeling

General equations in a liquid

$$\frac{\rho}{B} \frac{\partial p}{\partial t} - \rho \alpha \frac{\partial T}{\partial t} + \rho \vec{\nabla} \cdot \vec{v} = 0$$

$$\rho \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p + \mu \nabla^2 \vec{v} + (\lambda + \mu) \vec{\nabla} (\vec{\nabla} \cdot \vec{v})$$

$$\rho C_p \frac{\partial T}{\partial t} - \alpha T_0 \frac{\partial p}{\partial t} = \kappa \nabla^2 T$$

In a solid

$$\rho C_V \frac{\partial T}{\partial t} = \kappa \nabla^2 T - \alpha T_0 B \frac{\partial}{\partial t} \vec{\nabla} \cdot \vec{u} + r$$

$$\rho \frac{\partial^2 \vec{u}}{\partial t^2} = (\lambda_0 + \mu_0) \vec{\nabla} (\vec{\nabla} \cdot \vec{u}) + \mu_0 \nabla^2 \vec{v} + (\lambda + \mu) \vec{\nabla} (\vec{\nabla} \cdot \vec{v}) + \mu \nabla^2 \vec{v} - \alpha B \vec{\nabla} T + \vec{b}$$

Matrix form of the equations and the associated multi layers modeling.

$$\begin{bmatrix} \tilde{p} \\ v \\ q \\ T \end{bmatrix}_j = H_j(x) \begin{bmatrix} A_j \\ B_j \\ C_j \\ D_j \end{bmatrix} + \begin{bmatrix} S'_j \\ 0 \\ 0 \\ S'_j \end{bmatrix}$$

Layer 1	Layer 2	... Layer j ...	Layer N-1	Layer N
$\infty$	$l_1$	$l_{j-1}$	$l_j$	$l_{N-1}$
	Volumetric Source $S_1$	Volumetric Source $S_j$	Volumetric Source $S_{N-1}$	Average Temperature $T_0$

## Simulations designs and results

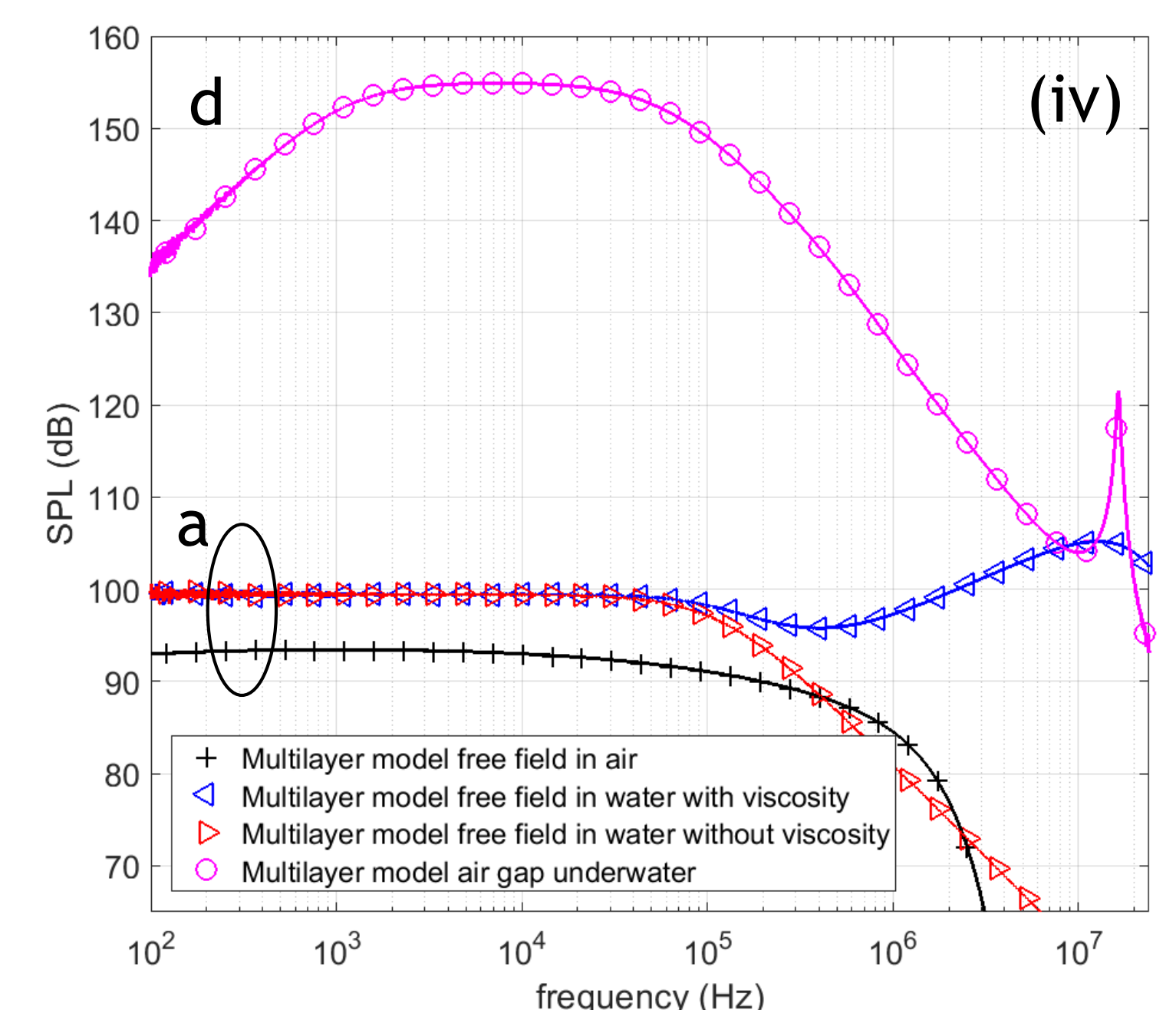
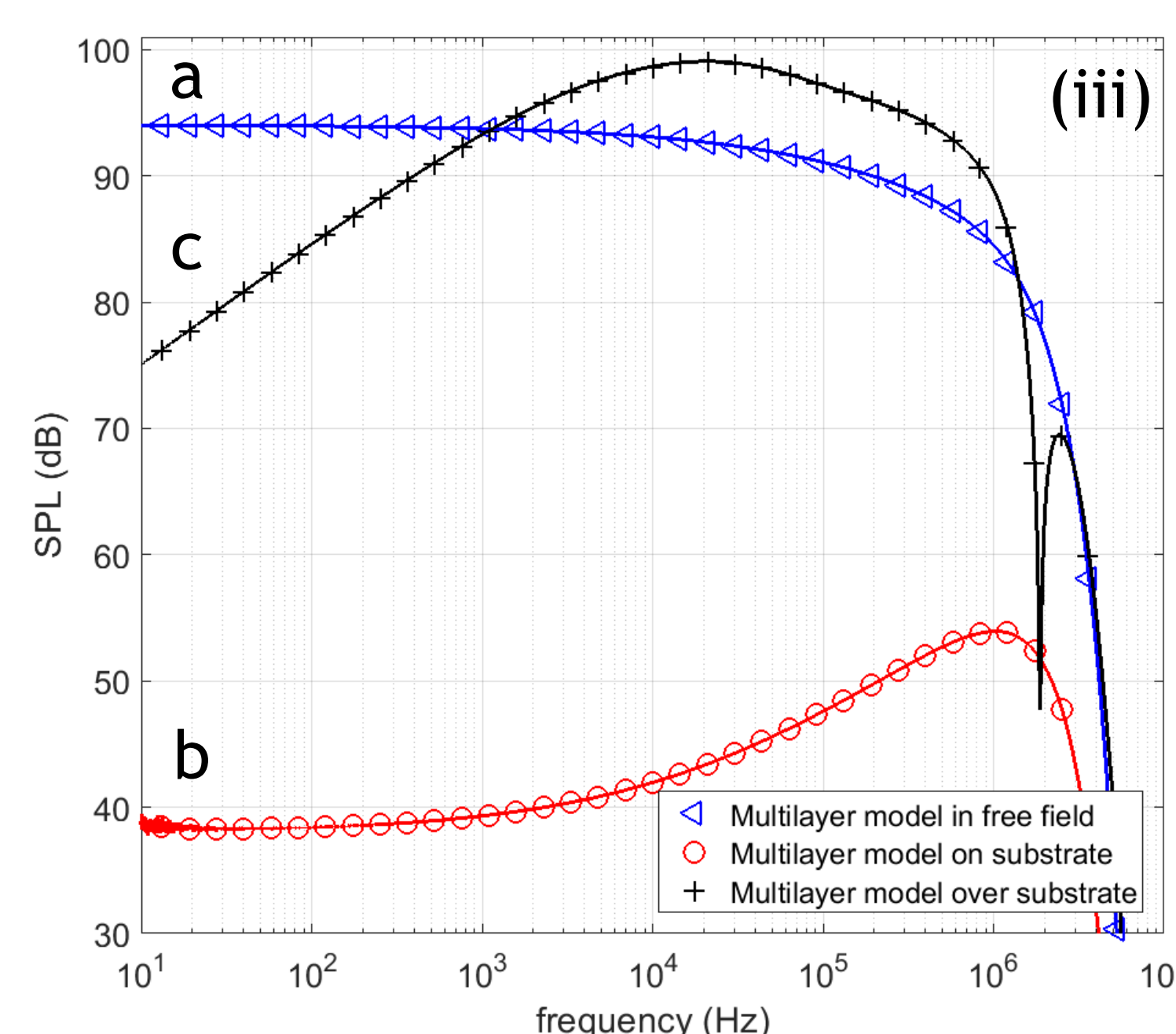
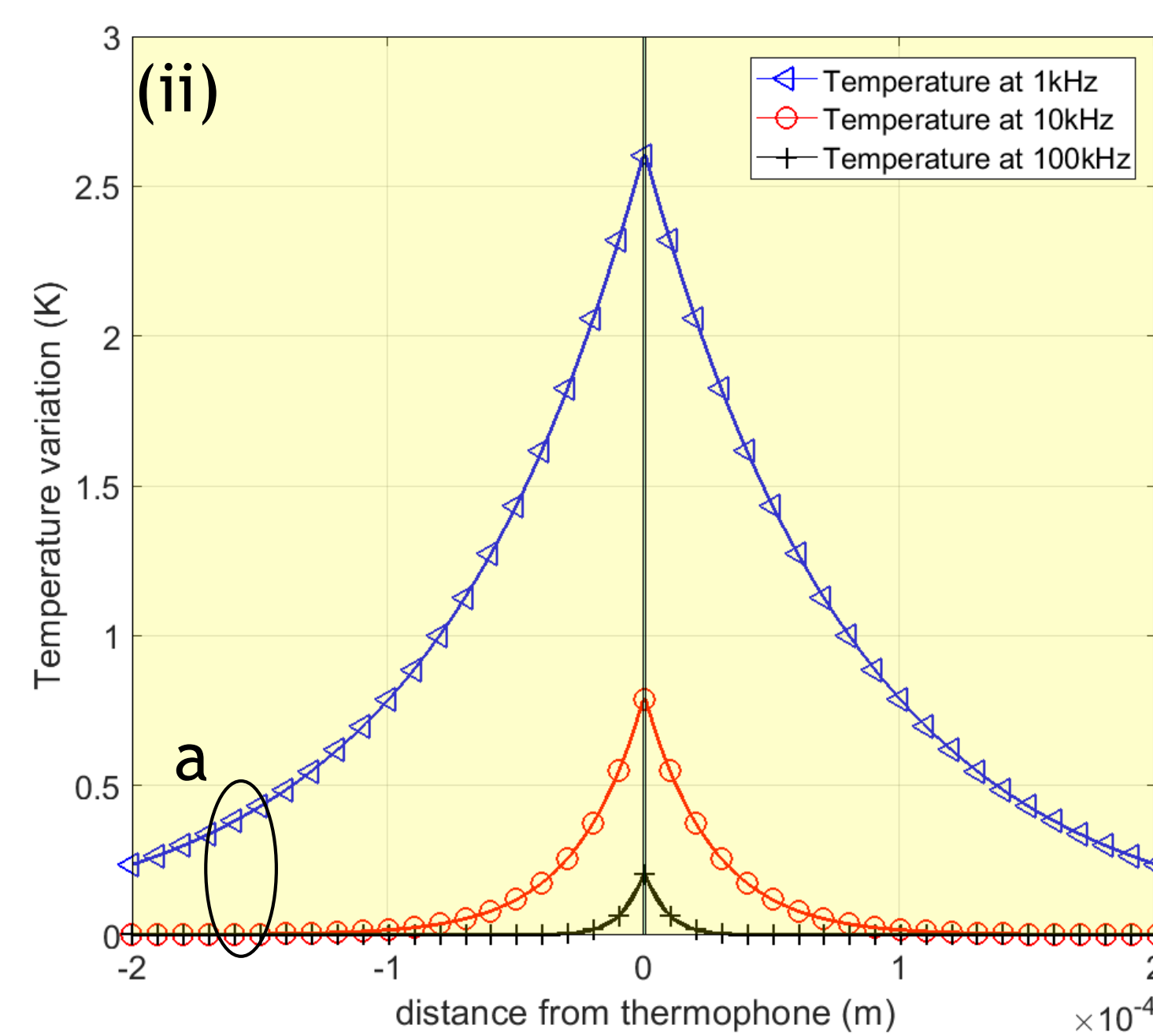
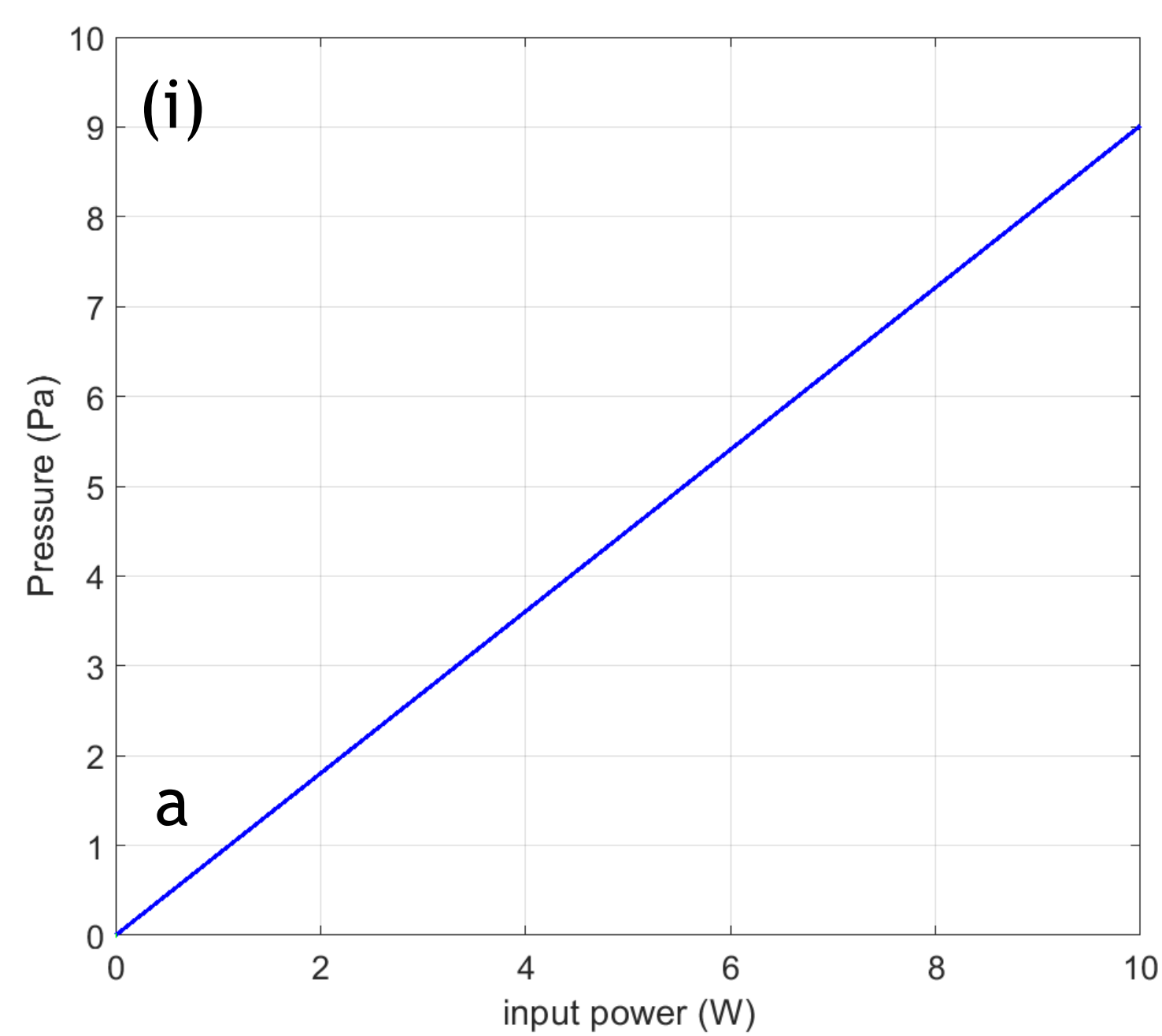
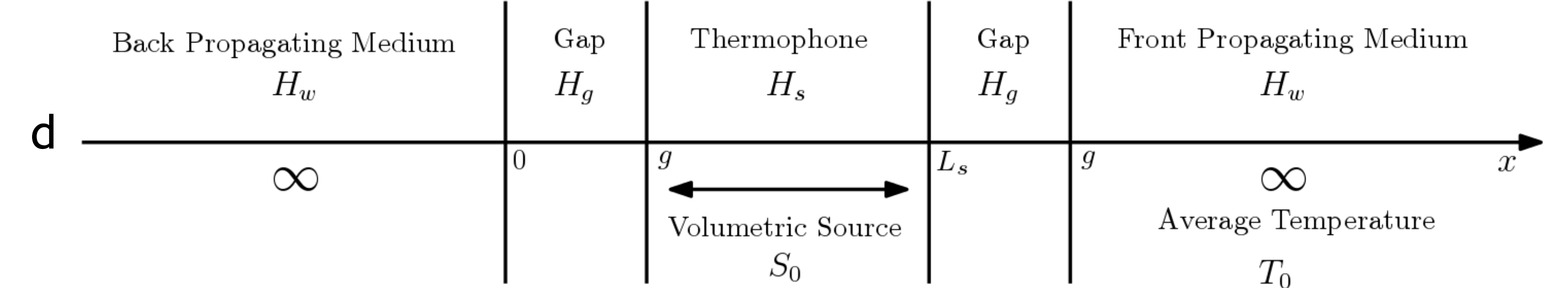
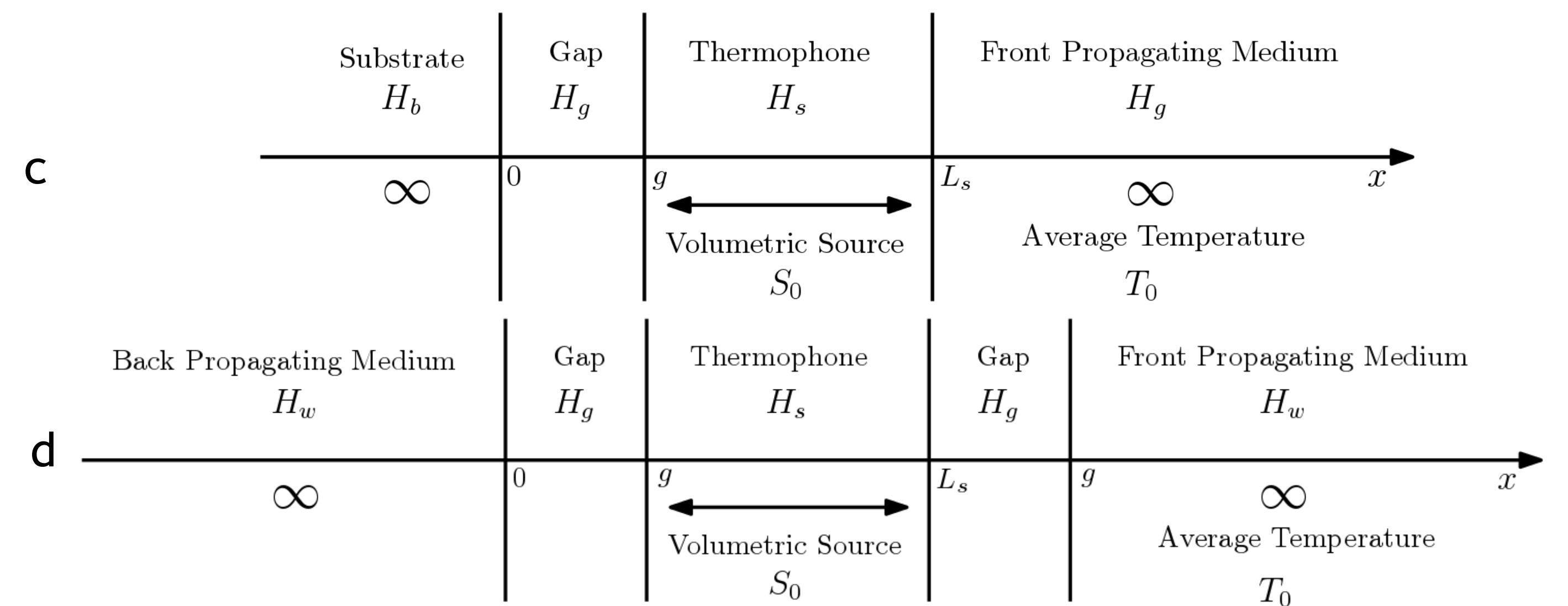
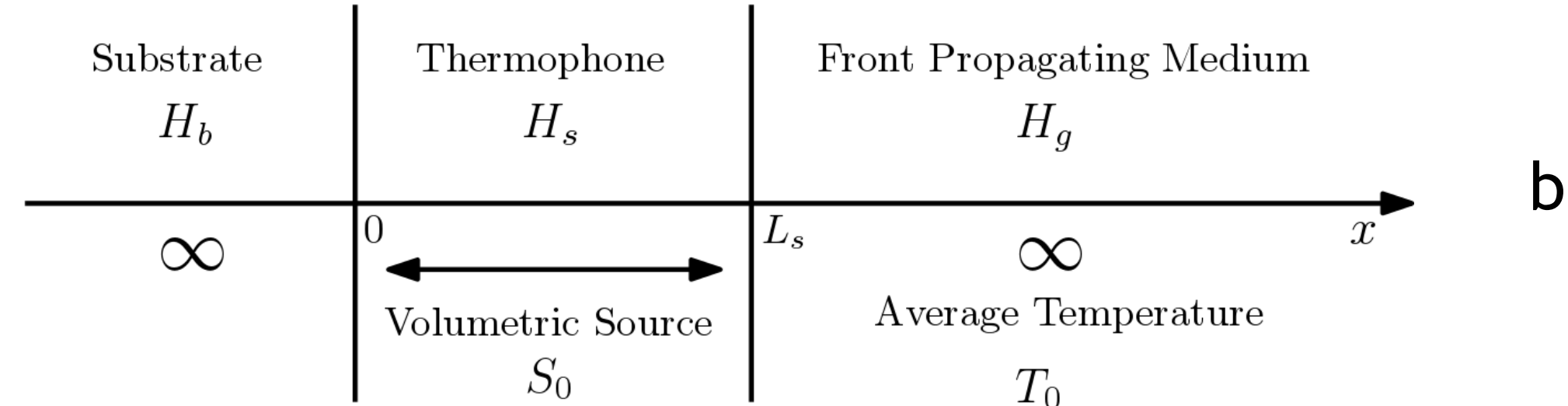
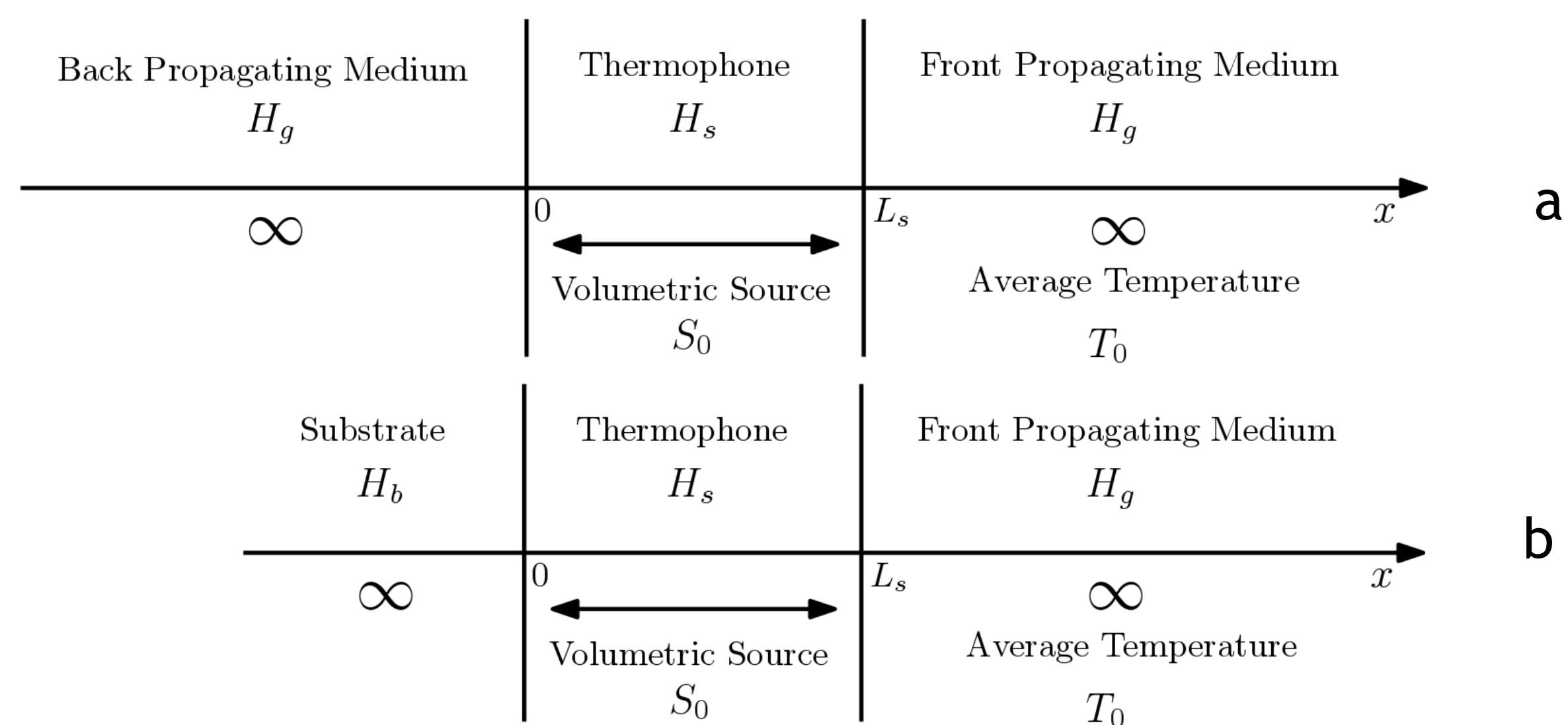


Fig.4: (i) Linear relation between input power and output pressure (ii) Variation of the temperature and the thermal layer length with frequency (iii) Sound Pressure Level (SPL) in air for different designs (iv) SPL in water for different designs, the SPL in free field in air is here for reference purposes. Spectrum assuming plane waves propagation.

## Conclusions and perspectives

- Unified thermoacoustic theory
- Flexible multi-layer modeling
- Model validated through comparison with literature models
- Need precise parameter measures for complex structures
- Need comparison with experiments
- Will use the model to improve thermophone design

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