



Two-temperature model for the thermoacoustic sound generation in porous materials

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I. Introduction: Thermoacoustic Principle

Sound Generation process

An alternative current is applied 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.



> Pros

- Generation process independent of the shape
- Wideband sound generation
- Flexible design

> Cons

- Not efficient generation compared to conventional speakers
- New, not yet optimized, not well understood technology

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I. Introduction: Thermoacoustic Principle

Thermophones Examples

- Thinfilm Thermophones (suspended nanowires, paper based, laser scribing...etc
- > Thick Thermophones (foam, sponge... etc)



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[2] Loeblein et al., Configurable 3D Boron Nitride-Carbon Artchitecture..., Small, 2014
 [3] Aliev et al., Alternative Nanostructures for Thermophones, ACS Nano 9, 2015

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II. Theory: One Temperature Model (1T)

Conservation Equations

> In a liquid

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

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

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

In a solid

-
$$\rho_s \frac{\partial^2 \vec{u}}{\partial t^2} = (\lambda_{0,s} + \mu_{0,s}) \vec{\nabla} (\vec{\nabla} \cdot \vec{u}) + \mu_{0,s} \nabla^2 \vec{u} + (\lambda_s \vec{v})$$



[4] Guiraud et al., Multilayer modeling of thermoacoustic sound generation for thermophone analysis and design, Journal of Sound and Vibration 2019



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II. Theory: One Temperature Model (1T)

Solutions

- > $T = Ae^{-ik_{ac}x} + Be^{+ik_{ac}x} + Ce^{-\theta_{th}x} + De^{+\theta_{th}x}$
- $\geq \tilde{p}(T), v(T), q(T)$

Boundary Conditions

> Continuity of : T, $\tilde{p}(T)$, v(T), q(T)

Semi infinite back and front mediums



[4] Guiraud et al., Multilayer modeling of thermoacoustic sound generation for thermophone analysis and design, Journal of Sound and Vibration 2019

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II. Theory: One Temperature Model (1T)

Performances & Limitations

- > Uniform distribution of the power, not realistic in a complex foam like geometry
- > The thickness of the thermophone only influence the **HCPUA** but the sound generation process remains solely at the surface



[4] Guiraud et al., Multilayer modeling of thermoacoustic sound generation for thermophone analysis and design, Journal of Sound and Vibration 2019

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Conservation Equations

> In a fluid

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

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

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

$$- \rho_s C_{V,s} \frac{\partial T_s}{\partial t} = \kappa_s \nabla^2 T_s + S_0$$



Solutions

 $T = Ae^{-ik_{ac}x} + Be^{+ik_{ac}x} + Ce^{-\theta_{th}x} + De^{+\theta_{th}x} \qquad T_s = Ee^{-\theta_{solid}x} + Fe^{+\theta_{solid}x} + T_{s,0}$ $\tilde{p}(T), v(T), q(T) \qquad P_s(T_s)$

6 constants (A,B,C,D,E,F) are necessary in each layers to fully define all the parameters



Boundary conditions

- > In the fluid (0 to N+1)
 - $T^+ = T^-$
 - $\widetilde{p}^+ = \widetilde{p}^-$
 - $v^+ = v^ rac{coupling term}{rac{coupling ter$
 - $q^+ = q^- + g(T_s T)$

-
$$T_s^+ = T_s^-$$

- $q_s^+ = q_s^- - g(T_s - T)$
 \frown coupling term

> At the Edges (0 and N+1)

- Semi Infinite Back Medium
- Semi Infinite Front Medium





Thick and Thin Thermophone at 3kHz: Temperature



Thick and Thin Thermophone at 3kHz: Particle Velocity



III. Analysis: Frequency and Power Spectrum

Comparison with experimental results from Aliev and al_[3]

[5] PCB Board Paper Graphene Sound Source Microphone (Earthworks M50) Dynamic Singal Analyzer (Agilent 35670A)





[3] Aliev et al., *Alternative nanostructures for thermophones*, ACS Nano 9, 2015[5] Tian an al, *Graphene-on-Paper Sound Source Devices*, ACS Nano 2011

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III. Analysis: Frequency and Power Spectrum

Thinfilm Thermophone Spectrum



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Thermophone

 x_2

 x_1

CNTsheet 2T th.

 10^{1}

itoPAN 1T th.

itoPAN 2T th.

Front Medium

Back Medium

III. Analysis: Frequency and Power Spectrum

Back Medium

 x_1

Thermophone

 L_l

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Front Medium

 x_2

17



Thick Thermophone Spectrum



DGA

[3] Aliev et al., Alternative nanostructures for thermophones, ACS Nano 9, 2015

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I. Theoretical models: Conclusions

One Temperature modelStrengths

- Consider the propagation of the wave in the solid
- Flexible design of thermophone with any number of different layers
- Working for planar, cylindrical and spherical waves

> Weaknesses

- Not adapted for thick, complex thermophone geometry

Two Temperatures model

- > Strengths
 - Novel thermophone theoretical model
 - More adapted for complex, thick, foam like thermophone geometry
 - Simpler model performing almost as well as the one temperature one for thin thermophones
- > Weaknesses
 - For now only for free field configuration with planar waves
 - Only the energy conservation equation is considered in the solid

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- None of them take the static raise of temperature in the pores into account for high input power

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Thank you for your attention

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I. Introduction: Context

Conventional Sound Generating devices

Electroacoustic transducer > Piezoelectric devices





- Low power driven devices
- Sound quality optimized for more than one century
- > Cons
 - Shape dependent devices
 - Mechanically resonant devices

https://www.researchgate.net/publication/277928278_A_Model_Updating_Technique_Based_on_the_Constitutive_Relation_Error_for_In_Situ_Identification_o f_Admittance_Coefficient_of_Sound_Absorbing_Materials https://fr.wikipedia.org/wiki/Pi%C3%A9zo%C3%A9lectricit%C3%A9

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Bonus: One Temperature Model (1T)

açon, en tout ou partie, ni divulgué à 2018 -Tous Droits réservés.

Model extension



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Multilayer for planar waves

Multilayer for cylindrical or spherical waves



II. Theory: Acoustic Diffraction

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Use of Rayleigh's integral to Compare Simulations and Experiments

Add the Diffraction using the calculated generated velocity

>
$$p_{FF}(X_r) = \frac{i\omega\rho_g}{4\pi} \int_S v(x_e) \frac{e^{-ikr}}{r} dS$$



Generate the Frequency and Power Spectrum of the Thermophone





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Thick and Thin Thermophone at 3kHz: Heat flux



Bonus: Thermal Layer (1T)



Bonus: Added Losses at the Boundaries

25

In a liquid $- \frac{\rho}{B} \frac{\partial p}{\partial t} - \rho \alpha_T \frac{\partial T}{\partial t} + \rho \vec{\nabla} \cdot \vec{v} = 0$ $- \rho \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p + \mu \nabla^2 \vec{v} + (\lambda + \mu) \vec{\nabla} (\vec{\nabla} \cdot \vec{v})$ $- \rho C_p \frac{\partial T}{\partial t} = \kappa \nabla^2 T + \alpha_T T_0 \frac{\partial p}{\partial t}$ Intermined and the second s

ck Medium Thermophone x_1 x_1 Front Medium x_{N+1} x

Thermophone

 $\cdots x_{N-1}$

 L_1

(N-1)

 x_N

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 x_{N+1}

(3)

 x_{A}

(2)

 x_3

(1)

22

Front

(_{N+)},

Medium

x

In a solid

Equations

$$- \rho_s C_{V,s} \frac{\partial T_s}{\partial t} = \kappa_s \nabla^2 T_s + S_0$$

> Heat flux continuity

$$-q^+ = q^- + g(T_s - T) - \beta_s T$$

Added coefficient for conduction, convection and radiation losses

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Back Medium

(0)

 x_1

Bonus: Coupling Coefficient Determination

Equations

Real total contact area between solid and air:

 $NSg = a\rho_s Vh$

Then
$$g=rac{a
ho_{s}Vh}{NS}\cong 10^{5}~W/m^{2}K$$

New Parameters

- a: Specific area of the foam (about 2000 m²/g) [6,7,8]
- h: Real heat film transfer coefficient (about 200 W/m²K) [9]

[6] Peigney et al., Specific Surface Area of Carbon Nanotubes and bundles of Carbon Nanotubes, Carbon 39, 2001
[7] Drieschner et al., High surface area graphene foams by chemical vapor deposition, 2D Materials, 2016
[8] Zhang et al., Porous 3D graphene-based bulk materials with exceptional high surface area and excellent conductivity for supercapacitors, Scientific Reports, 2013
[9] Silvestri et al., Thermal characterization of carbon nanotube foam using MEMS microhotplates and thermographic analysis, Nanoscale, 2016

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Bonus: Theoretical Parameters used



TABLE I. Parameters of the propagating medium (air).

	$ ho_s$	$C_{V,s}$	B_s	κ_s	L_l	L_s	A
	$[kg \cdot m^{-3}]$ [J	$\cdot kg^{-1} \cdot K^{-1}$]	[Pa]	$[W \cdot K^{-1} \cdot m^{-1}]$	[m]	[m]	[cm×cm]
CNT Sheet	1	716	1.11×10^{11}	50	18×10^{-6}	10×10^{-9}	Square 1.5×1.5
ITO PAN	220	606	1.65×10^{11}	310	5×10^{-6}	450×10^{-9}	Square 1.2×1.5
MWNT Sponge	30	716	1.11×10^{11}	100	100×10^{-6}	10×10^{-9}	Square 1×1
Graphene Sponge	2.75	660	1.44×10^{8}	6.3	800×10^{-6}	5×10^{-9}	Circle $d = 1.8$

TABLE II. Parameters of the thermophone materials used in the experiments and theoretical models. ³

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[3] Aliev et al., <i>Alternative nanostructures for thermophones</i> , ACS Nano 9, 2015
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