KTH ROYAL INSTITUTE OF TECHNOLOGY

Application of Slow Sound in Ducts

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Competence Center for Gas Exchange

CCGEx

”Charging for the future”

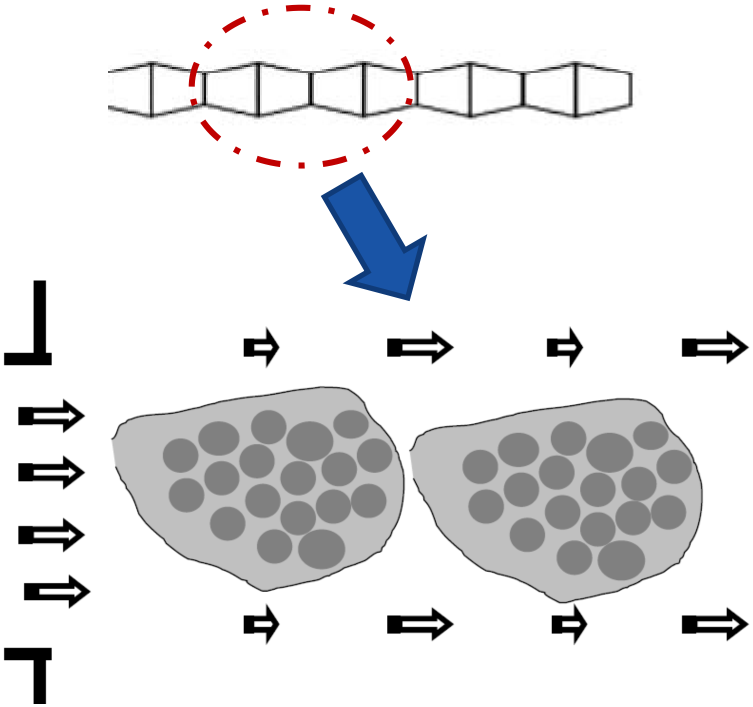
Energimyndigheten SCANIA VOLVO BorgWarner

Outline

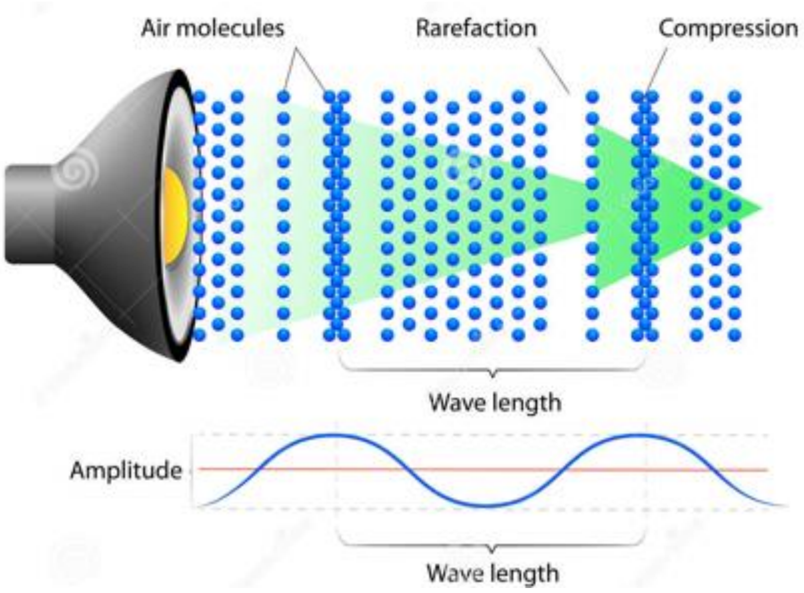
- **Introduction**
- **Model Development**
- **Acoustic Metamaterial ---- “Slow Sound”**
- **Acoustic Metamaterial ---- Agglomeration**
- **Experimental results**
- **Conclusions**

Introduction

Hydrodynamic



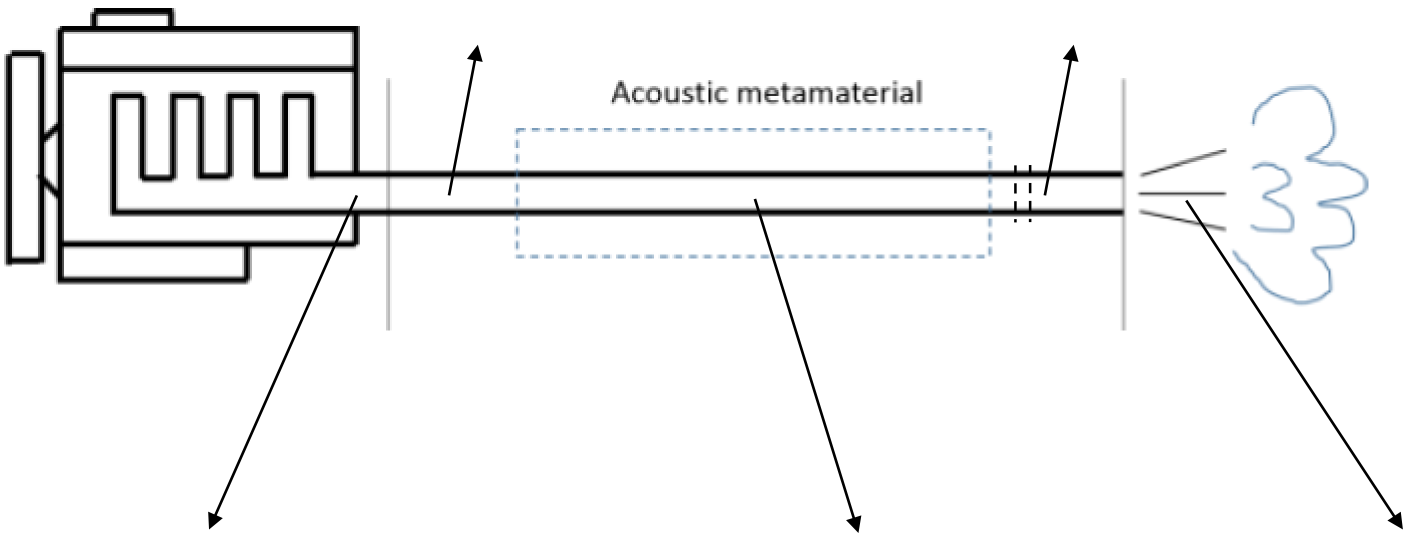
Acoustic



- Acoustic metamaterials

Introduction

Small particles fliter



Loud noise (>160 dB) Slow sound ---- agglomeration Cleaner exhaust

Model Establishment

$$\rho_p V_p \frac{dv_p}{dt} = F_d = 6\pi r_p \mu_f (v_f^{'} - v_p)$$

$$\frac{du_p^{'}}{d\tau} = \frac{1}{St}(u_f^{'} - u_p^{'})$$

$$v_f^{'} = V_a - V_{ac}\sin(kx - \omega t)$$

Acoustic particle velocity

$$\frac{dU_p^{'}}{d\tau} = \frac{1}{St}(U_a - U_{ac}\sin X - U_p^{'} - 1)$$

$$\beta = \frac{U_a - 1}{U_{ac}} = \frac{V_a - c}{V_{ac}} = \frac{c_0}{V_{ac}}$$

$$|\beta| \le 1$$

Numerical Example ---- Normal Sound

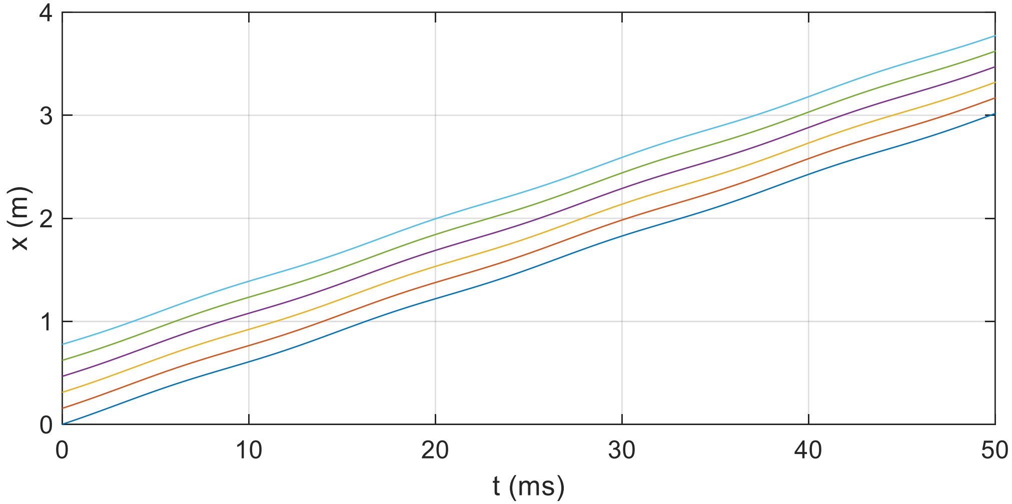
$$V_a = 60m/s$$

$$V_{ac} = 6.8m/s(160dB)$$

$$c = c_0 + V_a = 400(m/s)$$

$$\beta = \frac{U_a - 1}{U_{ac}} = \frac{V_a - c}{V_{ac}} = 50$$

Particle trajectory



Numerical Example ---- Slow Sound

$$V_a = 60 m/s$$

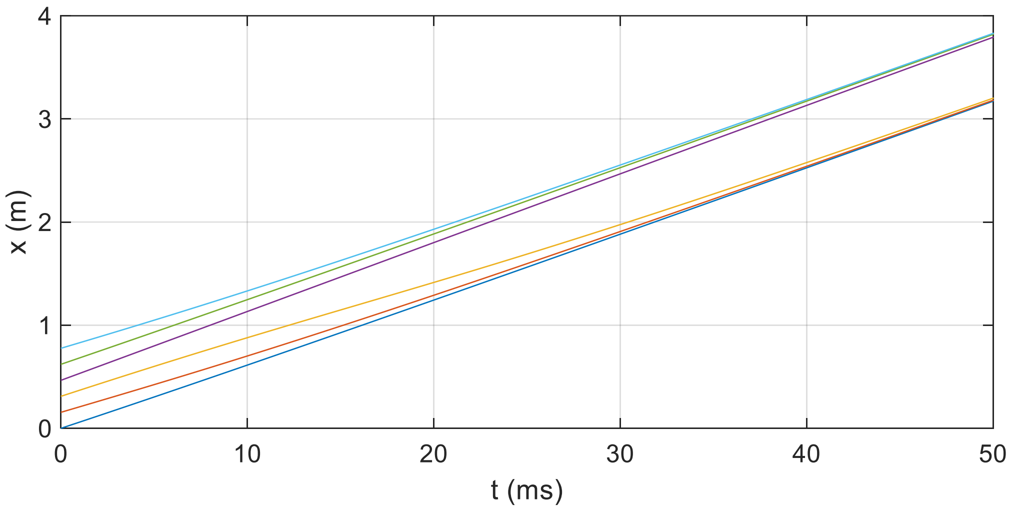
$$V_{ac} = 6.8 m/s (160 dB)$$

$$c \in [53.2, \quad 66.8] (m/s)$$

$$\beta = \frac{U_a - 1}{U_{ac}} = \frac{V_a - c}{V_{ac}} \in [-1,1]$$

$$c_0 \in [-6.8, \quad 6.8] (m/s)$$

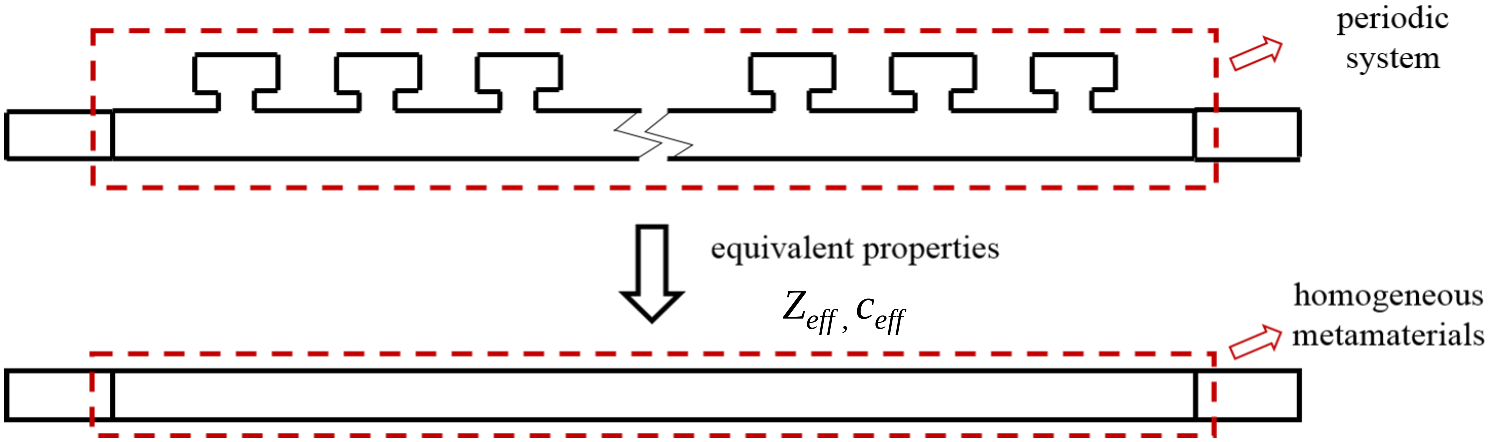
Particle trajectory



Acoustic Metamaterial

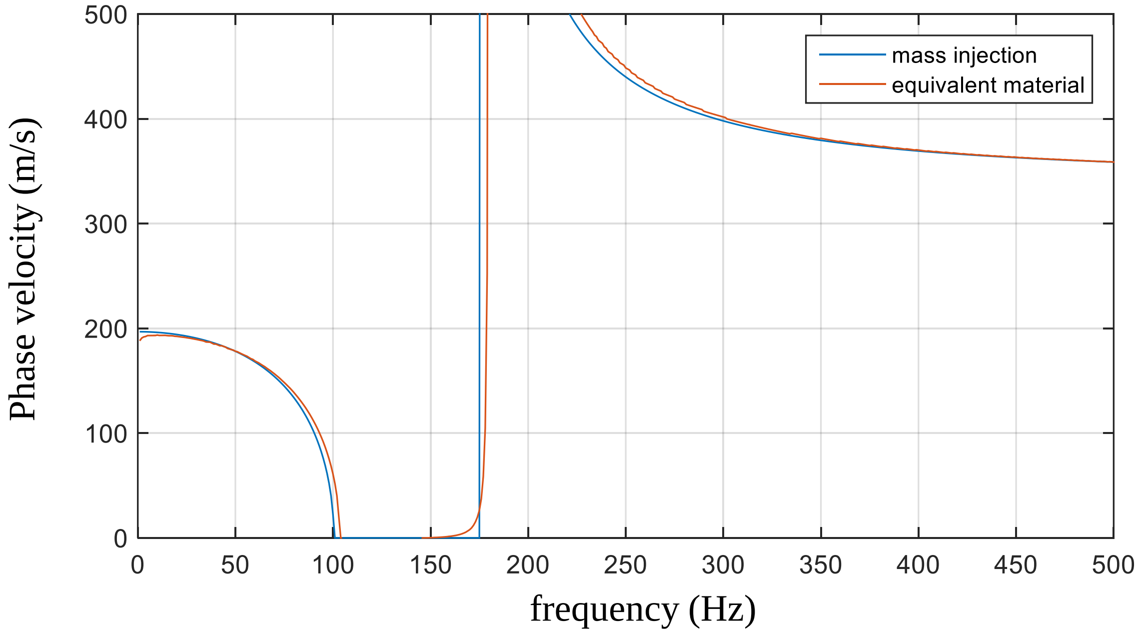
- artificially fabricated composite structures
- periodic structures
- equivalent homogeneous material ($\rho_{eff} < 0$, $\beta_{eff} < 0$)

$$c_{eff} = \sqrt{\beta_{eff} / \rho_{eff}}$$

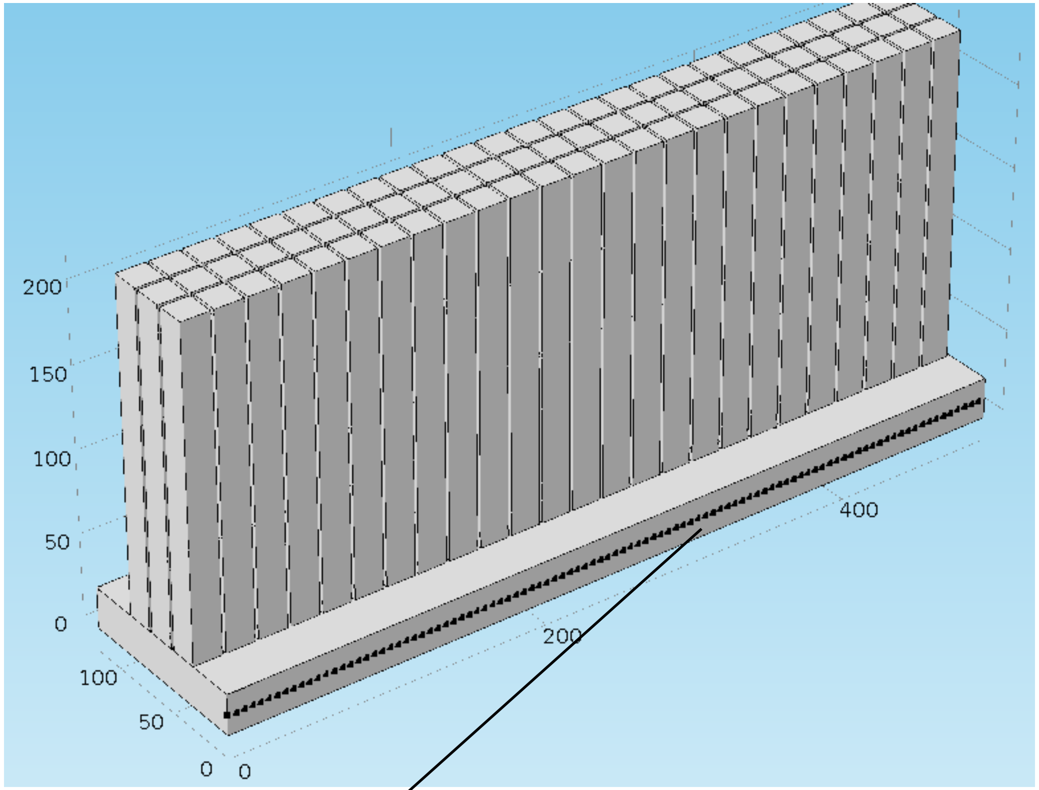


Slow Sound Calculation

- Equivalent material assumption
- “Mass injection”



Test Prototype



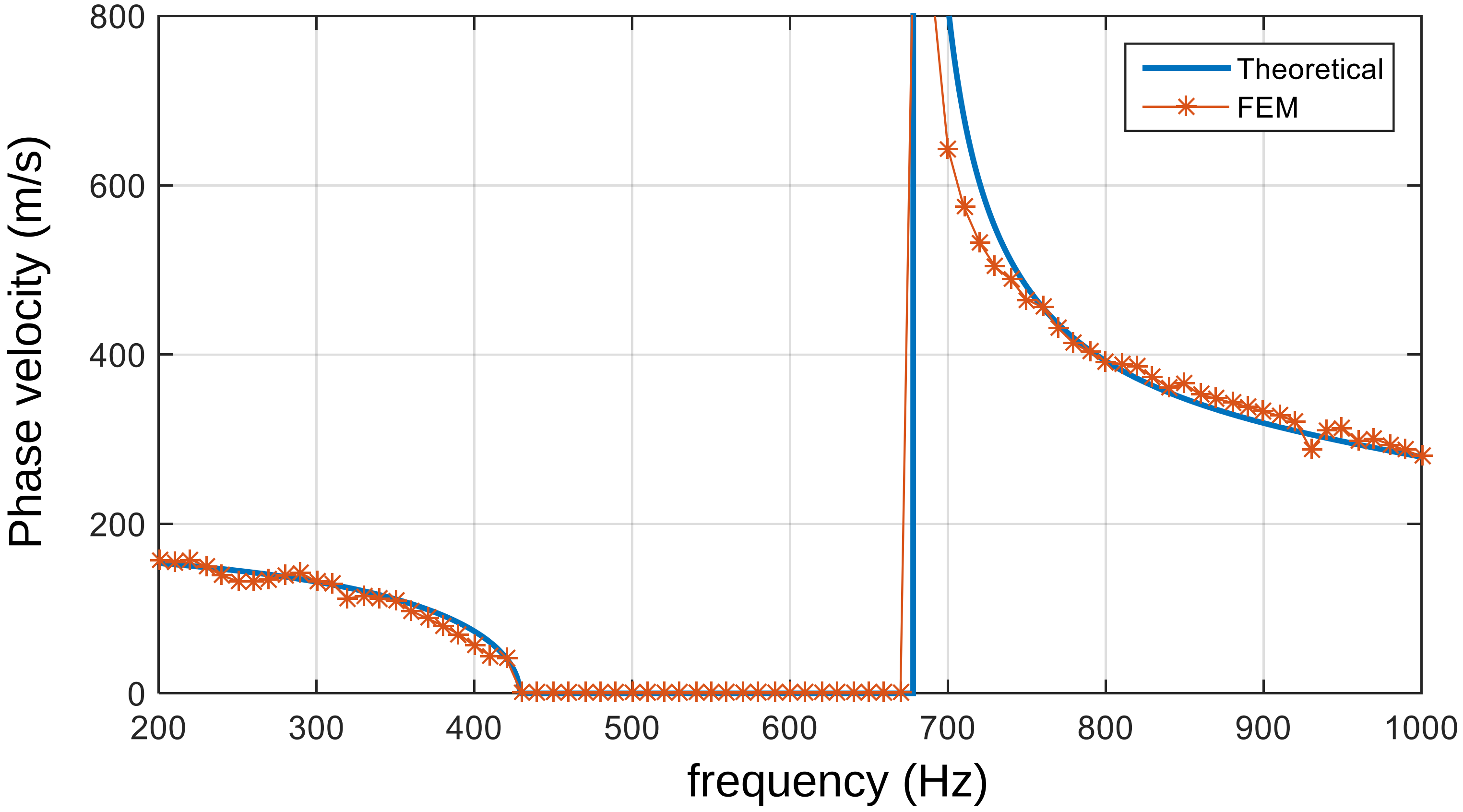
pressure

$$m' = -\rho_0 u_w' / d_h$$

$$k = \sqrt{(\omega / c_0)^2 - (\rho_0 i\omega / d_h Z_w)}$$

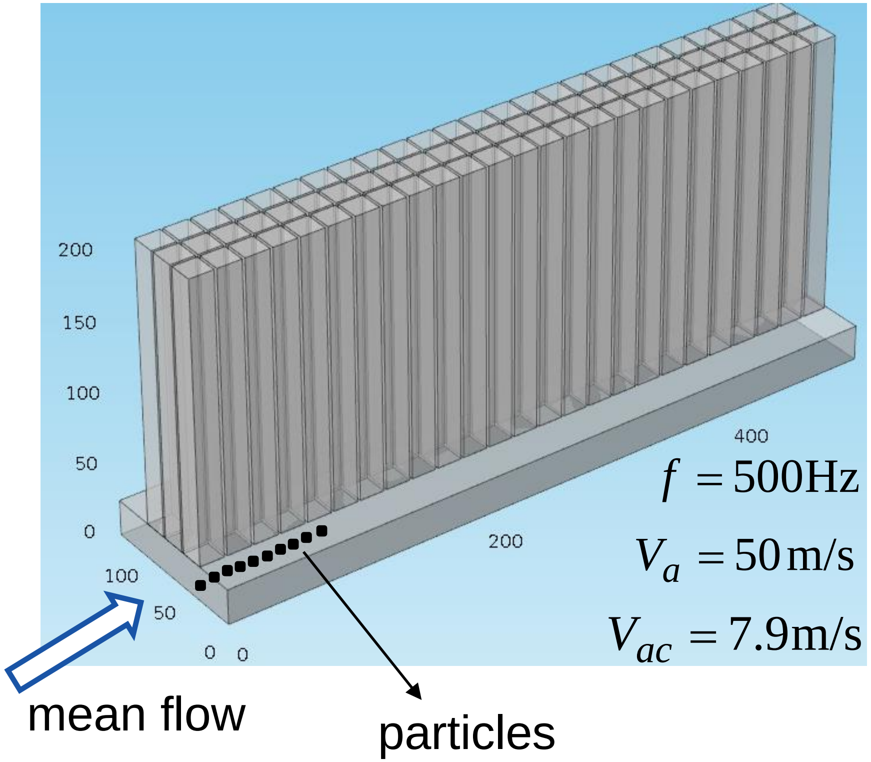
$$c_{ph} = \mathrm{Re}(\frac{\omega}{k}) = \mathrm{Re}(\frac{c_0}{\sqrt{1 + (\rho_0 c_0^2 / i\omega d_h Z_w)}})$$

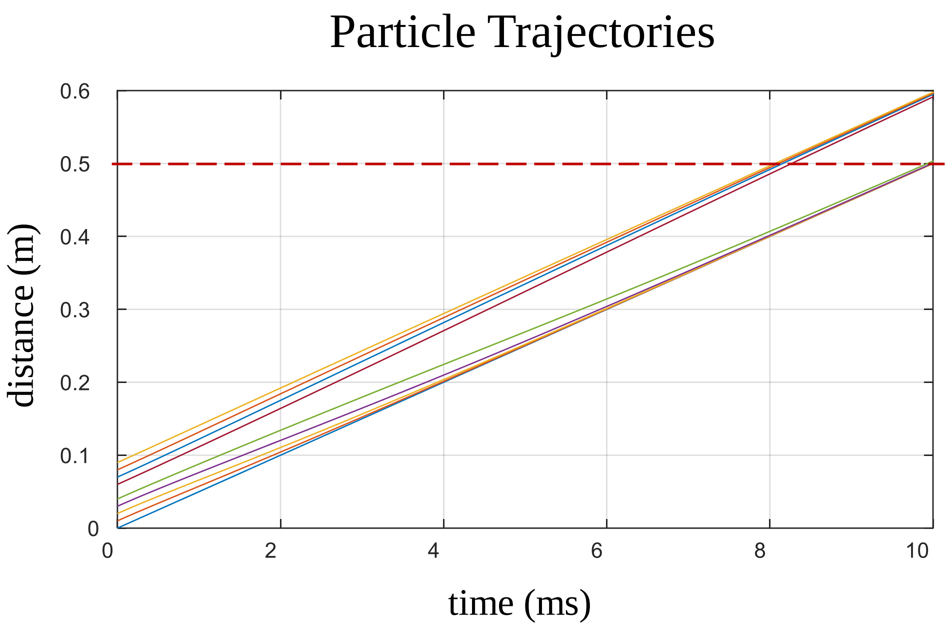
Slow Sound



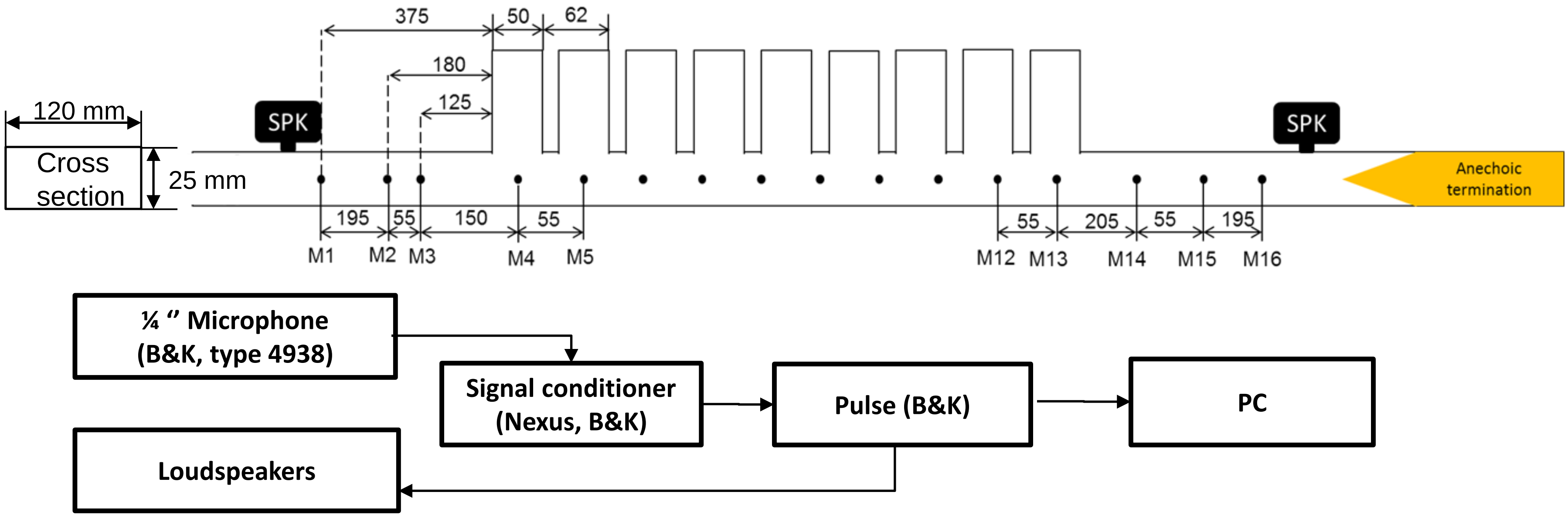
Phase velocity (m/s)
frequency (Hz)
Theoretical
FEM
800
600
400
200
0
200
300
400
500
600
700
800
900
1000

Agglomeration in Metamaterial





Experimental validation of slow sound



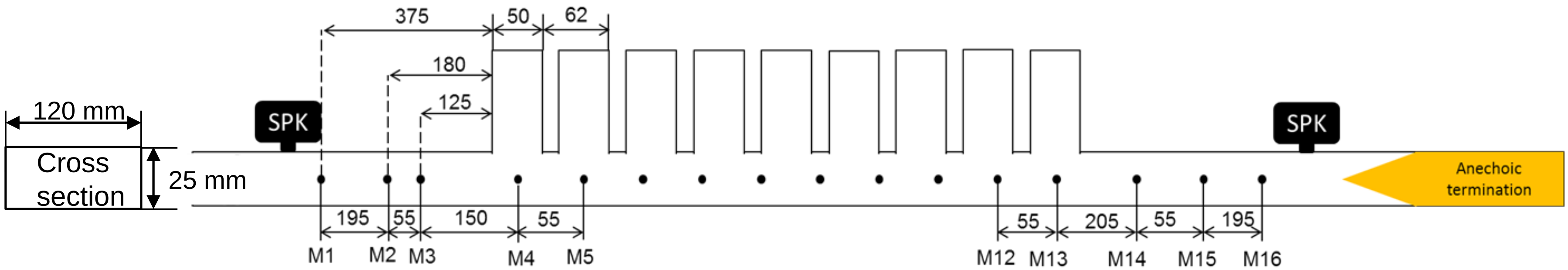
- Measurement condition
  - Excitation signal: Step sine signal: 50 Hz-1.4 kHz, Δf=10 Hz
  - Band pass filter: 20 Hz-3 kHz
- Signal processing condition
  - # of averages: 150, Signal processing: fs=3.2 kHz, df=1 Hz
- Two load method used

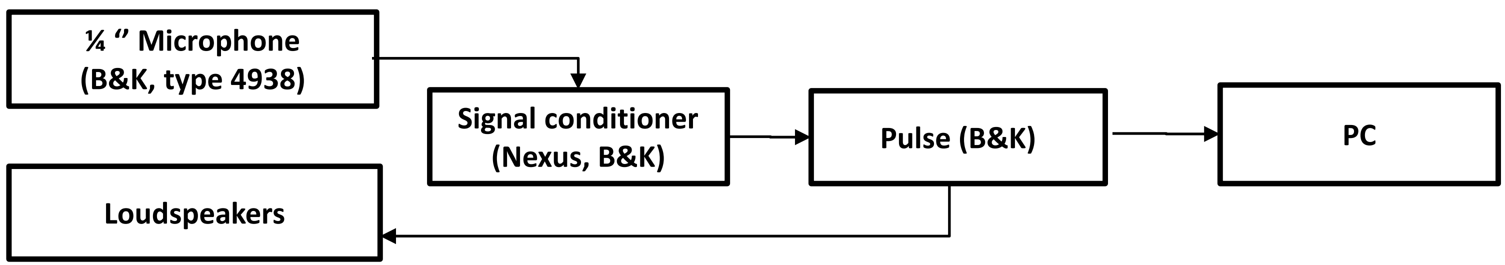
* De Prony BGR (1795)

** Jing XD et al.(2008)

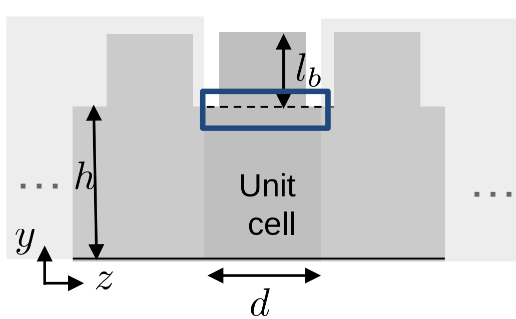
*** Jang SH & Ih JG (1998)

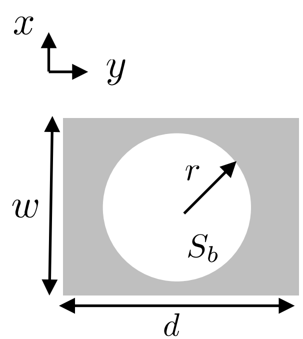
Experimental validation of slow sound





Geometric Information of used AMM





$S_b = \pi r^2$

$S_0 = wd$

$w = 120\ mm \quad l_b = 120\ mm$

$h = 25\ mm \quad d = 62\ mm$

$r = 25\ mm$

$l_e = l_b + \Delta l$

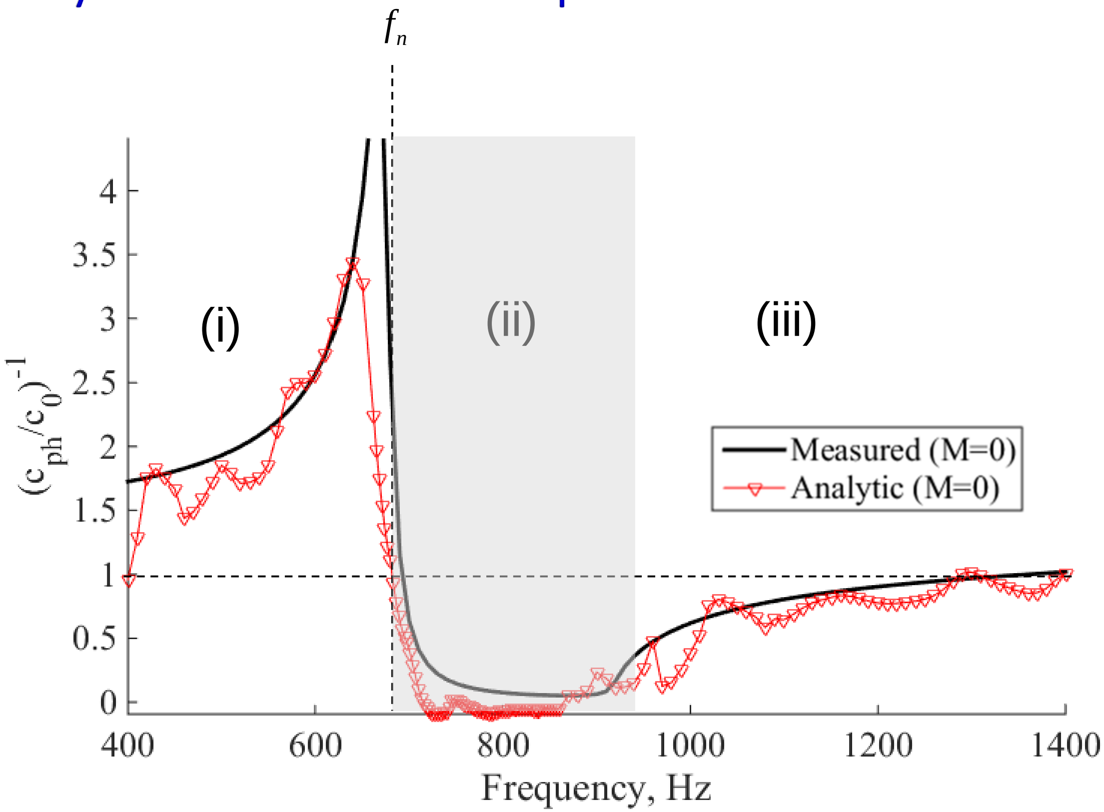
$\Delta l = 4.4\ mm$

$l_e = 0.124\ mm$

$$z_{eq} = \frac{p}{u_y} = z_{sb}\frac{S_0}{S_{sb}} \quad \text{where} \quad z_{sb} = -j\rho c_0 cot(kl_e)$$

Phase speed w/o mean flow

- Used of Prony's method* to decompose 0th & 1st order mode (10 mic.)



(i) ***f*<690 Hz** : Slow phase speed

(ii) 690 <f<920 Hz: Sound attenuation is dominant

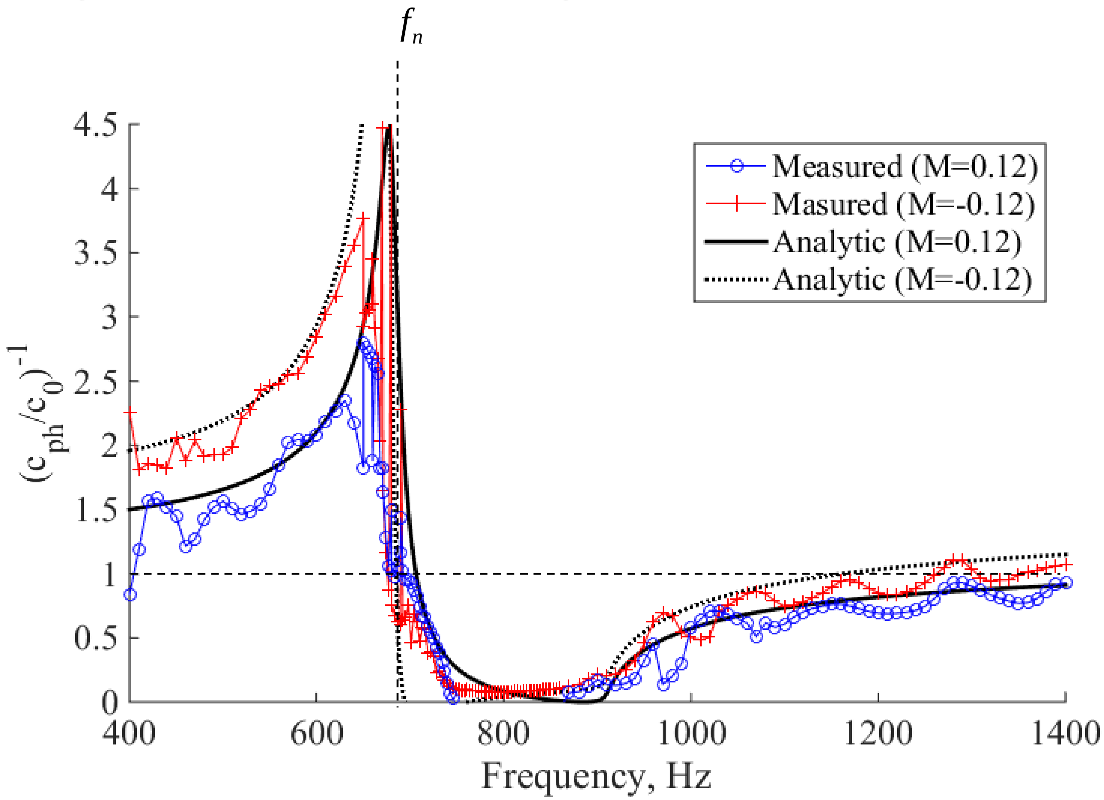
(iii) **f>920 Hz:** Fast phase speed converging to c_0 along freq.

* De Prony BGR (1795)

** Jing XD et al.(2008)

Phase speed with mean flow

- Used of Prony's method* to decompose 0th & 1st order mode (10 mic.)



Overall tendency is similar to the no flow case.

M=0.12: Source @ upstream
M=-0.12: Source @ downstream

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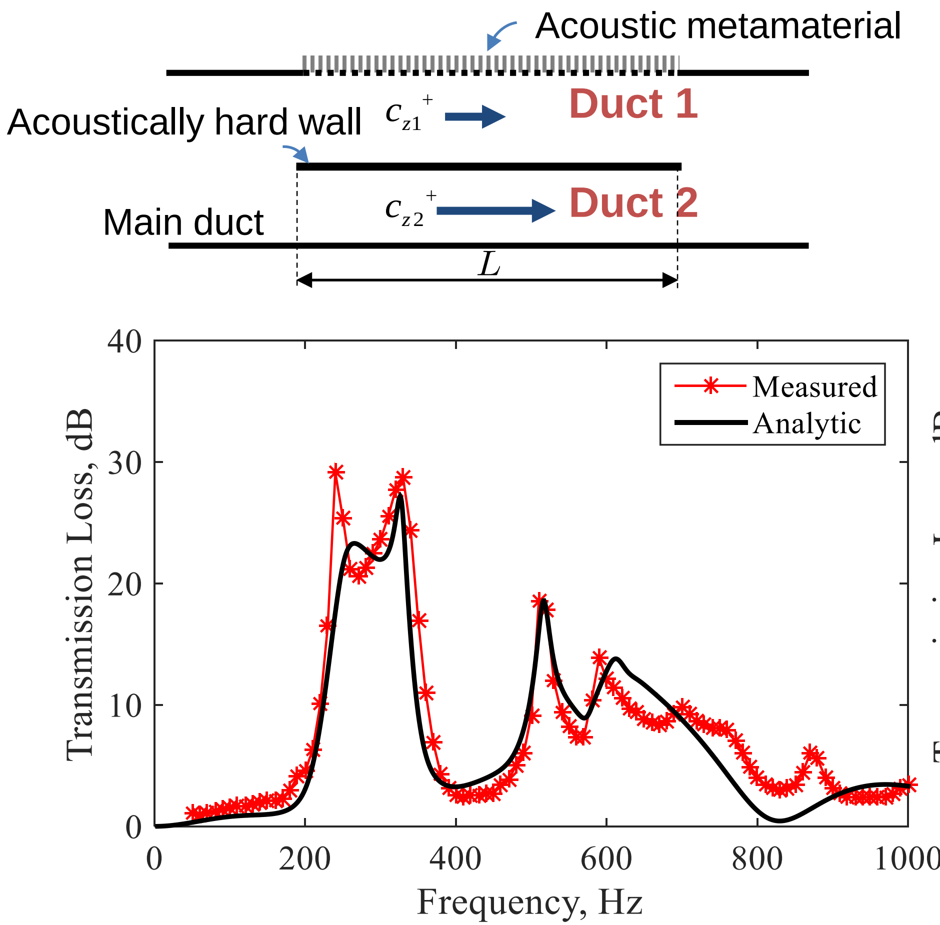
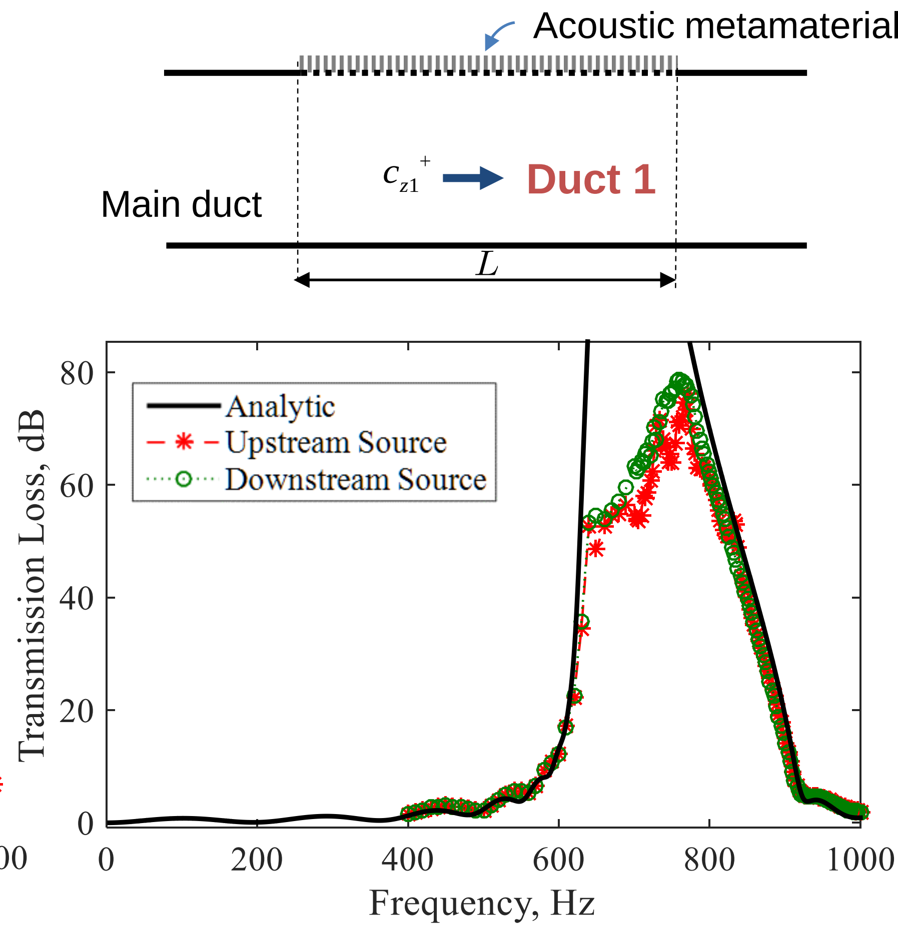
Comparison of transmission loss





- High TL in low frequency (200-400 Hz) by parallel arrangement
- Relatively broad band noise reduction because of combination effect of parallel duct sys. & AMM

Conclusions

- Particle agglomeration through an acoustic method proposed
- Theoretical model developed
- Realization of acoustic metamaterial by quarter wave resonators
- Good agreement between analytical model and experimental results
- Experiment on particle agglomeration so-far not successful

References

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Thank you for your attention!

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