Acoustic signal in laser additive manufacturing processes

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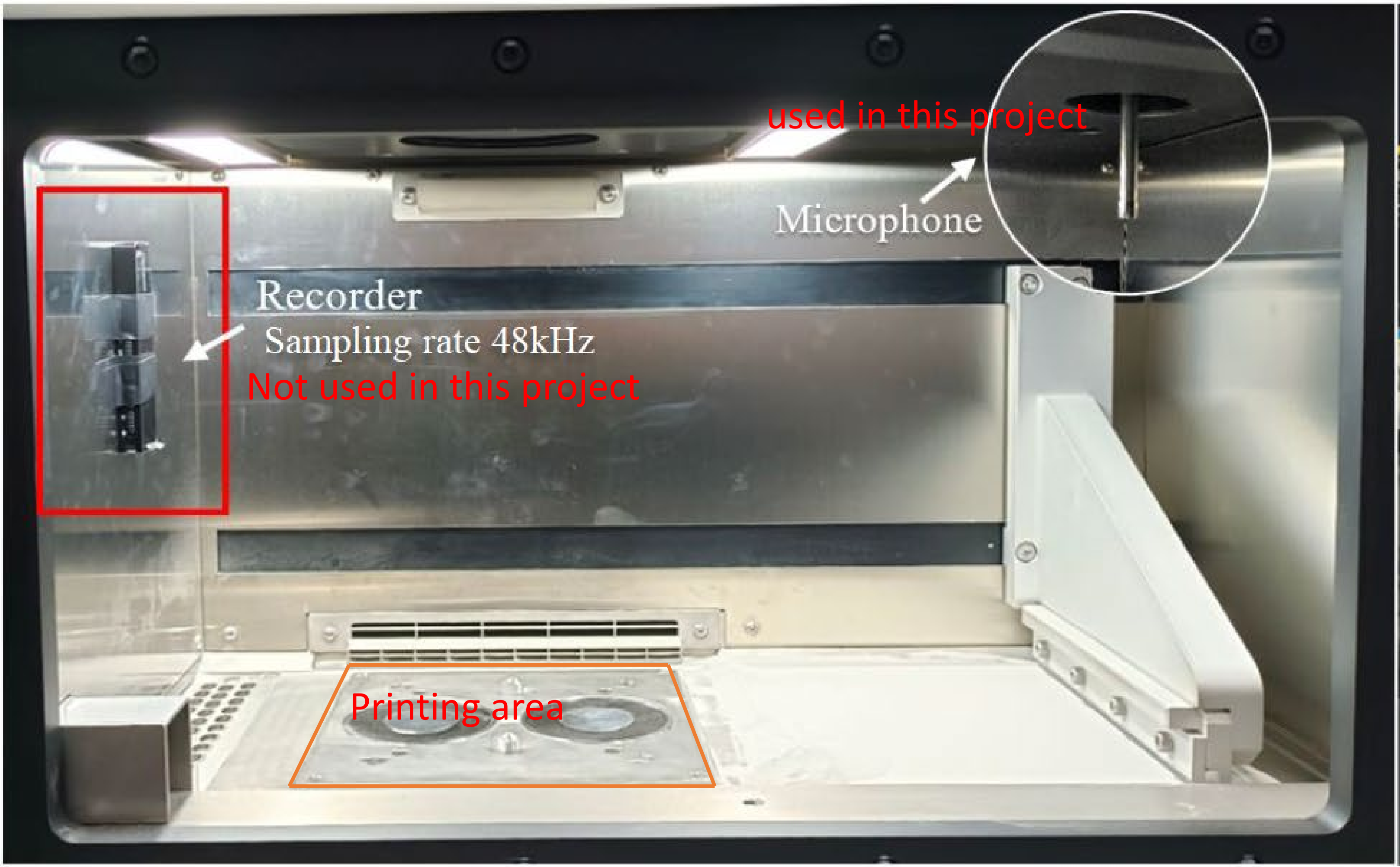
Experimental setup



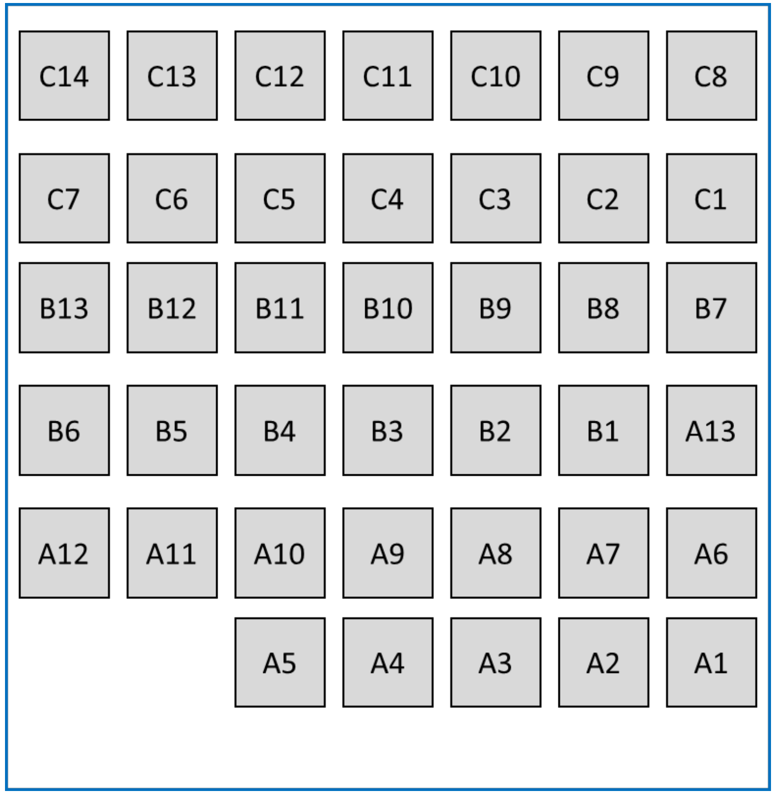
BSWA MPA401
20-70kHz

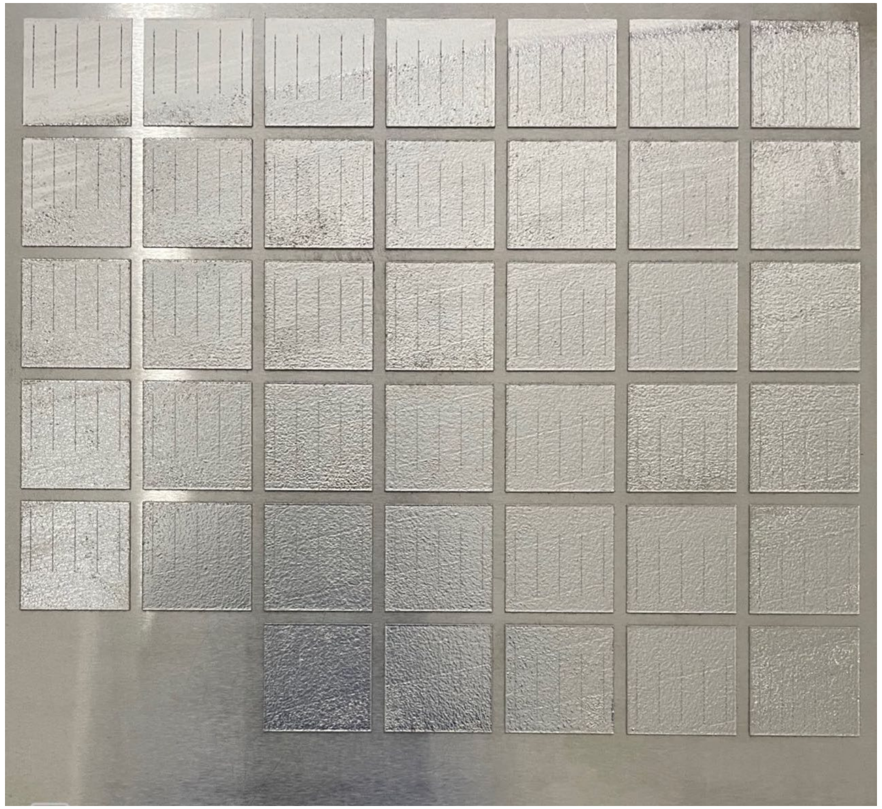
CBS003 BNC-SMB

ADLINK USB2405/2AI
128KS/S

Sample preparation

- Print ten-layers square-shape first and then print 5 single tracks on the top surface of each square
- Each square is printed with different sets of laser parameters (laser power & scan speed, listed in a later slide)
- Gather the acoustic data when printing single tracks

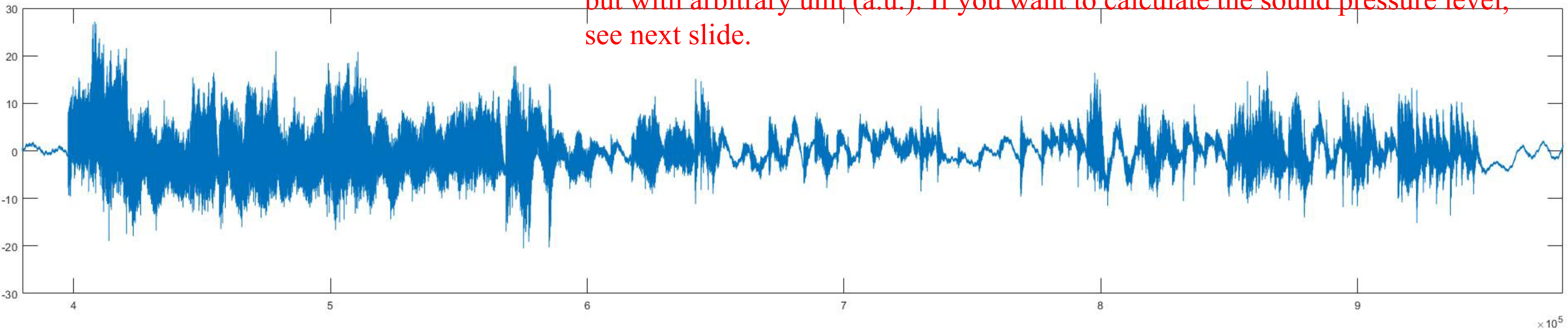




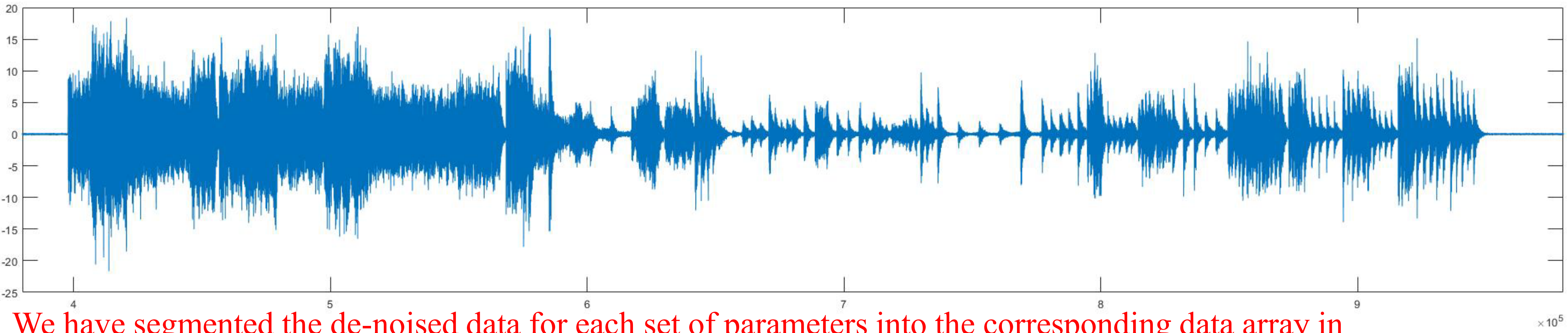
Single tracks

Raw data (dataRaw.mat)

X represents time sequence with the sampling rate of 128 kHz.
Y is the voltage variation of the sensor, which represents sound pressure level but with arbitrary unit (a.u.). If you want to calculate the sound pressure level, see next slide.



After de-noising the raw data (dataDenoise.mat)



We have segmented the de-noised data for each set of parameters into the corresponding data array in dataSingleTracks.mat. The data array names and the laser parameters are listed in last slide.

SOUND PRESSURE LEVEL calculation

- Sound pressure level(SPL/LP):

$$SPL = 20\, log_{10}\left(\frac{p}{pref}\right)$$

pref：20μPa

- Open circuit sensitivity: VPP (mV/Pa)
- Instantaneous sound pressure:

$$p = \frac{V(mV)}{VPP(mV/Pa)} = \frac{V}{VPP}Pa$$

Our microphone sensitivity: 5mV/Pa

- **RMS Voltage：V_{RMS} (mV)**

$$V_{\mathrm{RMS}} = \sqrt{\frac{1}{n}(V_1^2 + V_2^2 + \cdots + V_n^2)}$$

$$SPL = 20\, log_{10}\left(\frac{\frac{V}{VPP}Pa}{20\mu Pa}\right)$$

$$= 20\, log_{10}\left(\frac{V}{VPP}\right) + 20\, log_{10}\left(\frac{1}{20\mu}\right)$$

$$= 20\, log_{10}\left(\frac{V}{VPP}\right) + 94dB$$

Manufacturing parameters for each sample

Hatch spacing (0.15mm) and nominal layer thickness (0.04mm)

data name	Laser power (W)	Scan speed (mm/s)
A1	350	1200
A2	400	600
A3	250	600
A4	250	1000
A5	400	1000
A6	375	1050
A7	350	700
A8	200	500
A9	350	500
A10	200	400
A11	200	700
A12	250	500
A13	400	1200

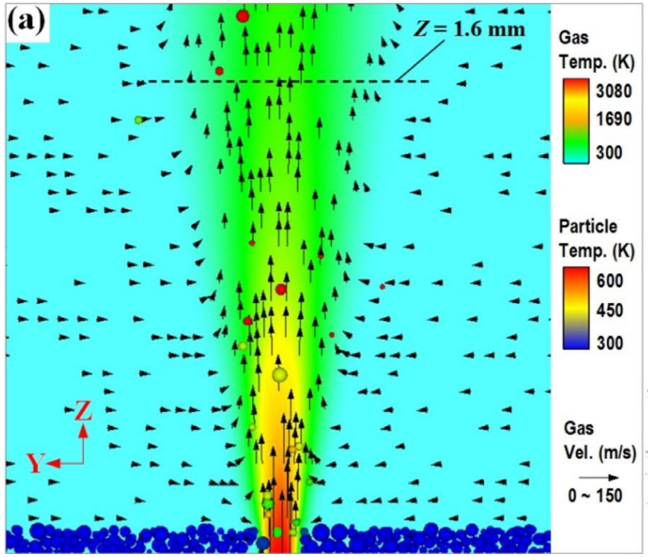
data name	Laser power (W)	Scan speed (mm/s)
B1	200	200
B2	300	1000
B3	150	600
B4	400	800
B5	150	500
B6	300	800
B7	150	400
B8	300	700
B9	400	1600
B10	330	V_{B10}=???
B11	150	200
B12	300	500
B13	400	2000

data name	Laser power (W)	Scan speed (mm/s)
C1	150	800
C2	200	1600
C3	200	2000
C4	250	400
C5	250	1600
C6	250	2000
C7	300	1200
C8	300	2000
C9	P_{c9}=???	600
C10	330	1050
C11	350	800
C12	350	1600
C13	P_{c13}=???	700
C14	P_{c14}=???	V_{c14}=???

Physical foundation / physics-based methods

Acoustic sources:

1. **Keyhole flow and vapor jet (approximately 100-*700* m/s)**
2. **Ambient gas flow (1-10 m/s)**
3. **Powder and spatter collision (0.1-10 m/s)**
4. Cracking (absent??)
5. Environmental noise (de-noised??)
6. Others



Frequency ranges? Relative SPL?

May provide guidance to the data-driven methods

Physical foundation / physics-based methods

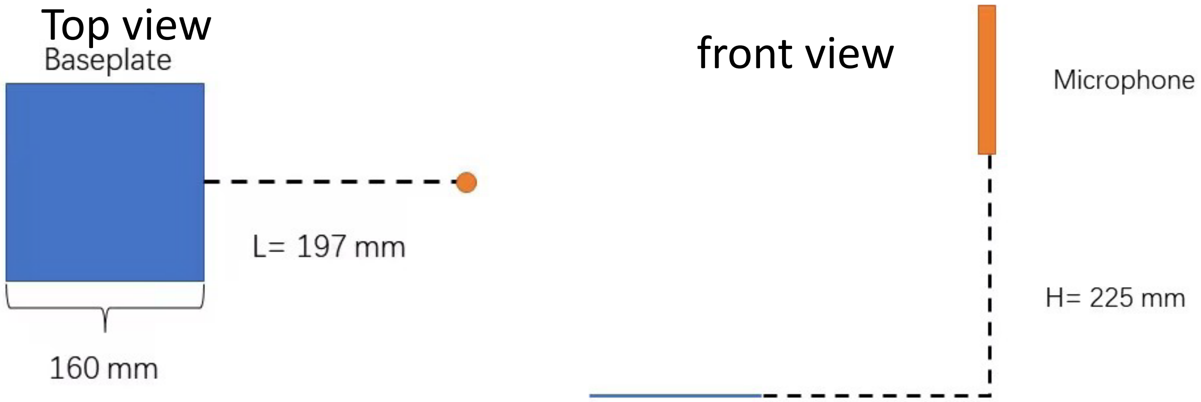
May also be considered in the data-driven methods

Propagation:

1. **Damping, Bass's equation**

$$\alpha = \frac{20f^2}{\ln(10)}\left[\left(\frac{1.84\cdot 10^{-11}}{\left(\frac{T_0}{T}\right)^{1/2}\frac{p}{p_0}}\right)+\left(\frac{T_0}{T}\right)^{5/2}\left(\frac{0.1068}{0.7809}\frac{e^{-3352/T}f_{r,N}}{f^2+f_{r,N}^2}\right)\right]$$

2. Reverberation, Sabine's equation



$$T_{60} = \frac{24\ln(10)}{c_s}\frac{V}{\sum_i A_i\alpha_i}$$

The volume V and surface area A of the chamber can be calculated.
The speed of sound c_s in nitrogen is 350 m/s
The absorption coefficient α_i is 0.01

K. Gutknecht, M. Cloots, R. Sommerhuber, K. Wegener, Mutual comparison of acoustic, pyrometric and thermographic laser powder bed fusion monitoring, Materials & Design 210 (2021) 110036.

Acoustic emission due to powder and spatter collision

Theory

L. L. Koss and R. J. Alfredson, Transient sound radiated by spheres undergoing an elastic collision, *Journal of Sound and Vibration*, 27 (l) (1973) 59-75.

$$
\begin{aligned}
&p(r,\theta,t)\\
&= \frac{\rho_0 f a^3 \cos\theta}{4m(b^4+4l^4)} \frac{1}{2r^2}\Bigg\{\bigg(\frac{2r}{a}\\
&-1\bigg)\left[(8l^3 b - 4lb^3)\cos bt' + 8b^2 l^2 \sin bt'\right]\\
&-4b^4 \sin bt' - (8l^3 b + 4lb^3)\cos bt'\\
&+\left(\frac{2r}{a}-1\right)\left[(4b^3 l - 8bl^3)\cos lt'\right.\\
&\left.-(8bl^3+4b^3 l)\sin lt'\right]e^{-lt'}\\
&+\left[(4b^3 l - 8bl^3)\cos l\left(t'-\frac{\pi}{2l}\right)\right.\\
&\left.-(8bl^3+4b^3 l)\sin l\left(t'-\frac{\pi}{2l}\right)\right]e^{-lt'}\Bigg\}\\
&+\frac{\rho_0 f a^3 \cos\theta}{2mr^2}\sin bt'
\end{aligned}
$$

$$t' = t - \frac{r-a}{c}$$

$$b = \frac{\pi}{\tau}$$

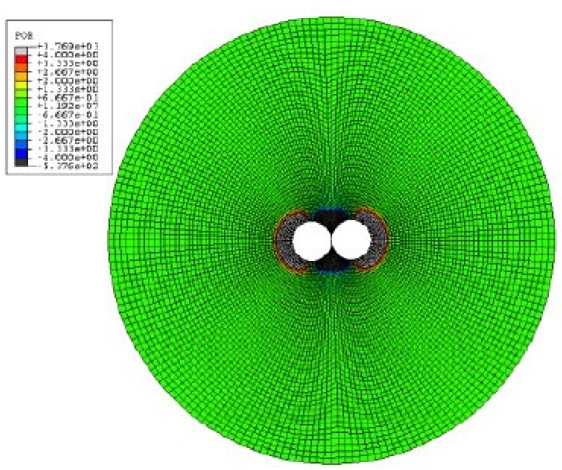
$$l = \frac{c}{a}$$

$$f = k\left[\frac{5mv_0^2}{8k}\right]^{0.6}$$

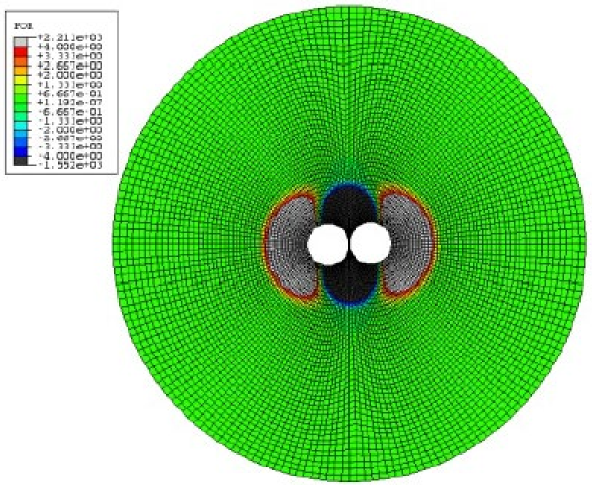
$$k = \frac{4}{3}\left[\frac{E}{2(1-\nu^2)}\right]\left(\frac{a}{2}\right)^{0.5}$$

ρ_0 is the density of air,
a is the radius of spheres,
m is the mass of spheres.
d is the duration of impact
c is the speed of sound in air
v_0 is the impact velocity,
E is the Young's modulus
v is the Poisson's ratio.

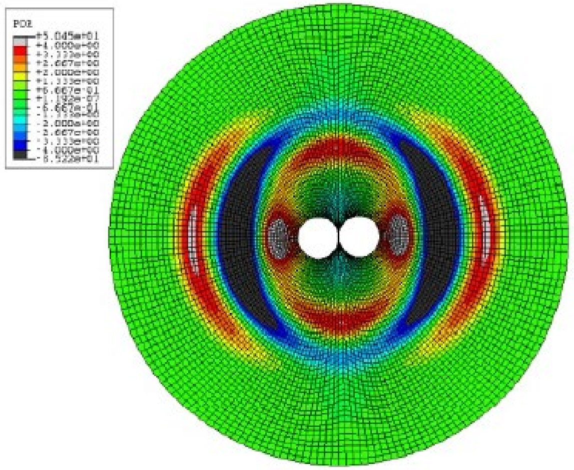
Acoustic emission due to powder and spatter collision



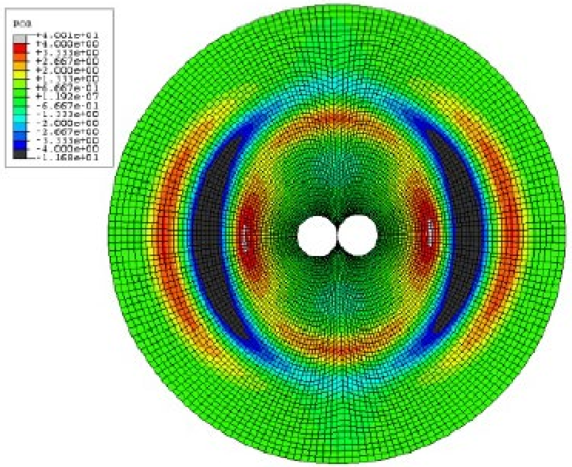
Time = 0.1 ms



Time = 0.2 ms



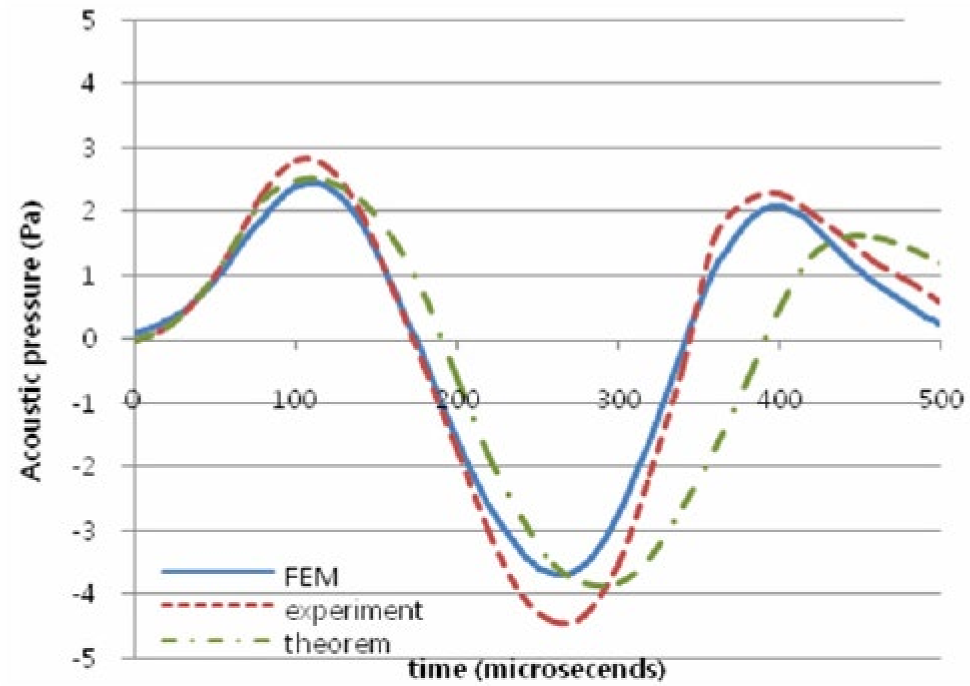
Time = 0.5 ms



Time = 0.6 ms

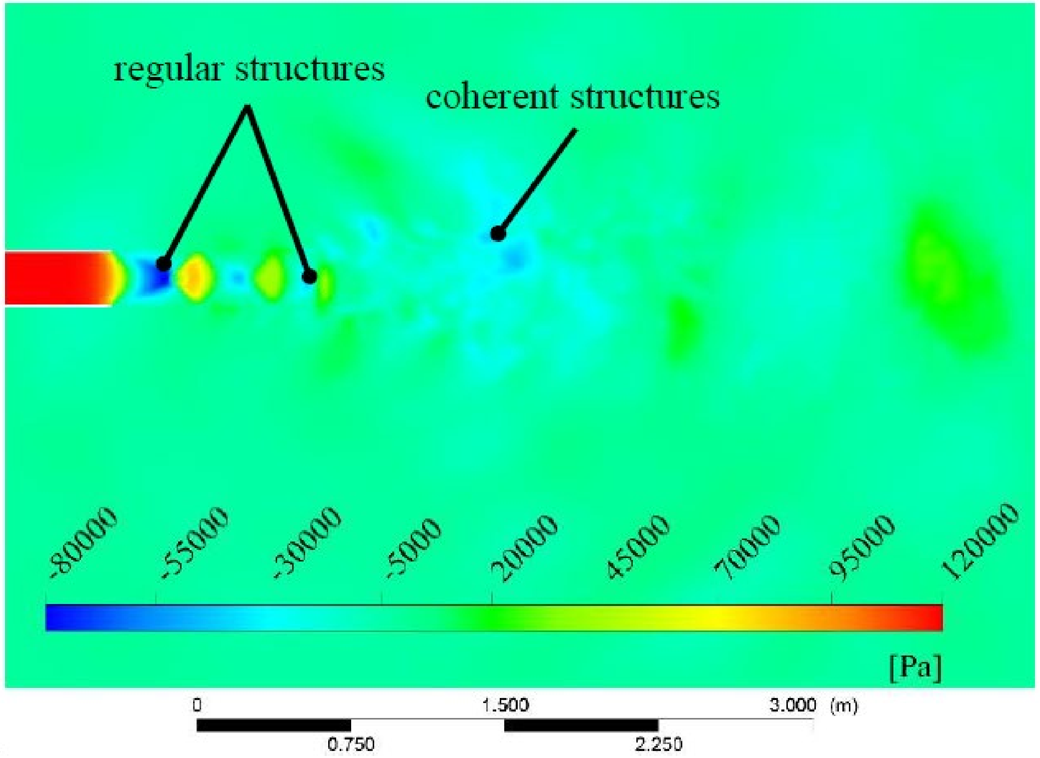
Simulation

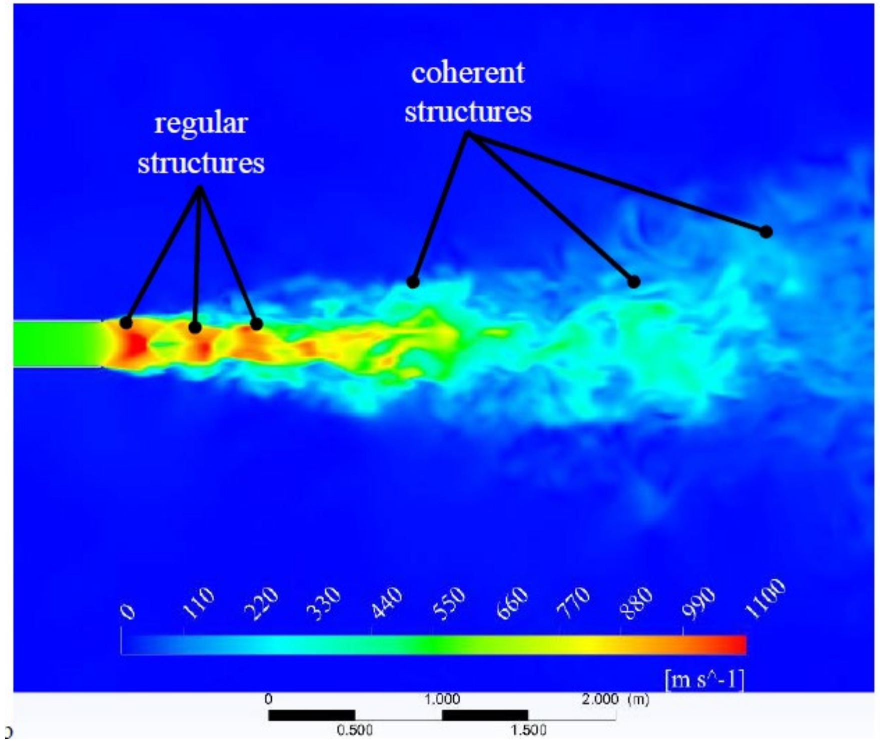
Mehraby, K., Khademhosseini Beheshti, H., & Poursina, M. (2011). Impact noise radiated by collision of two spheres: Comparison between numerical simulations, experiments and analytical results. *Journal of mechanical science and technology*, *25*(7), 1675-1685.



Acoustic emission due to vapor jet

- Simulation



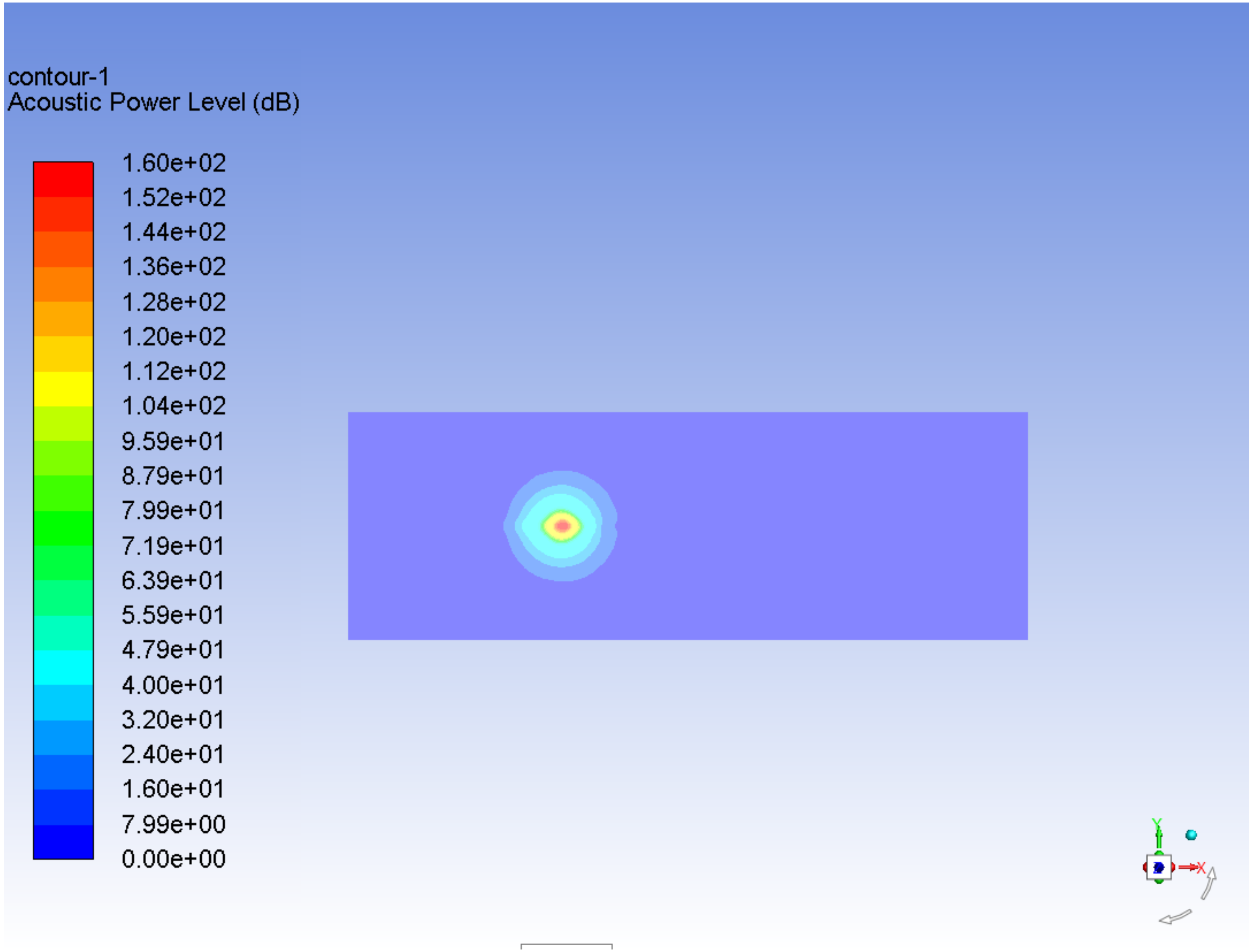


Acoustic emission due to vapor jet

Simulation of vapor blowing

vapor blowing speed

Scan speed
(translational speed of
vapor jet)



Data-based methods

Key considerations:

- Data volume and methods: Machine learning methods that require large numbers of data are not suitable.
- Evaluate the accuracy: R^2; divided the datasets into training & testing data
- Input-output pair:
  - ➢input variables p, v, p/v, p/vhL, p/vD…? How many?
  - ➢Output: peak/average/overall SPL, frequency …? How many?
  - ➢Balance between complexity and effectiveness!