Microphone Array Measurements for High-speed Train

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- Railway Noise
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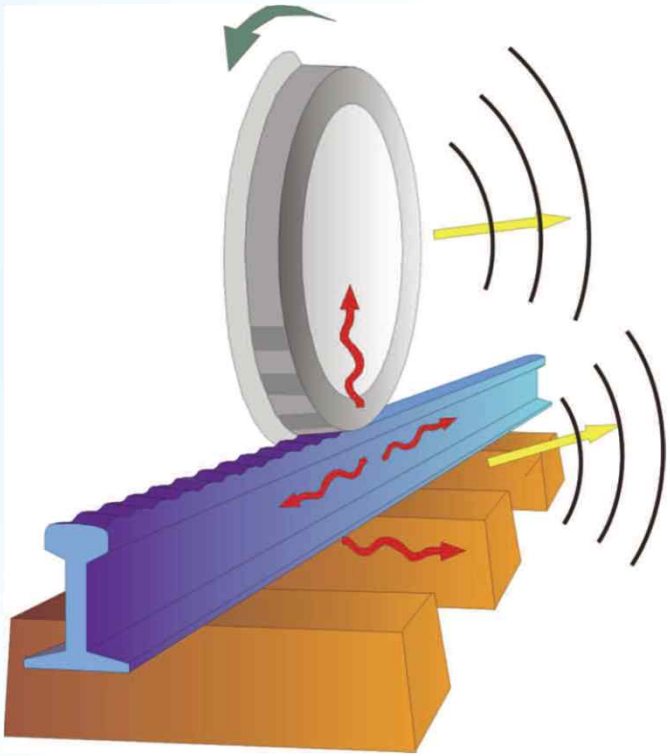
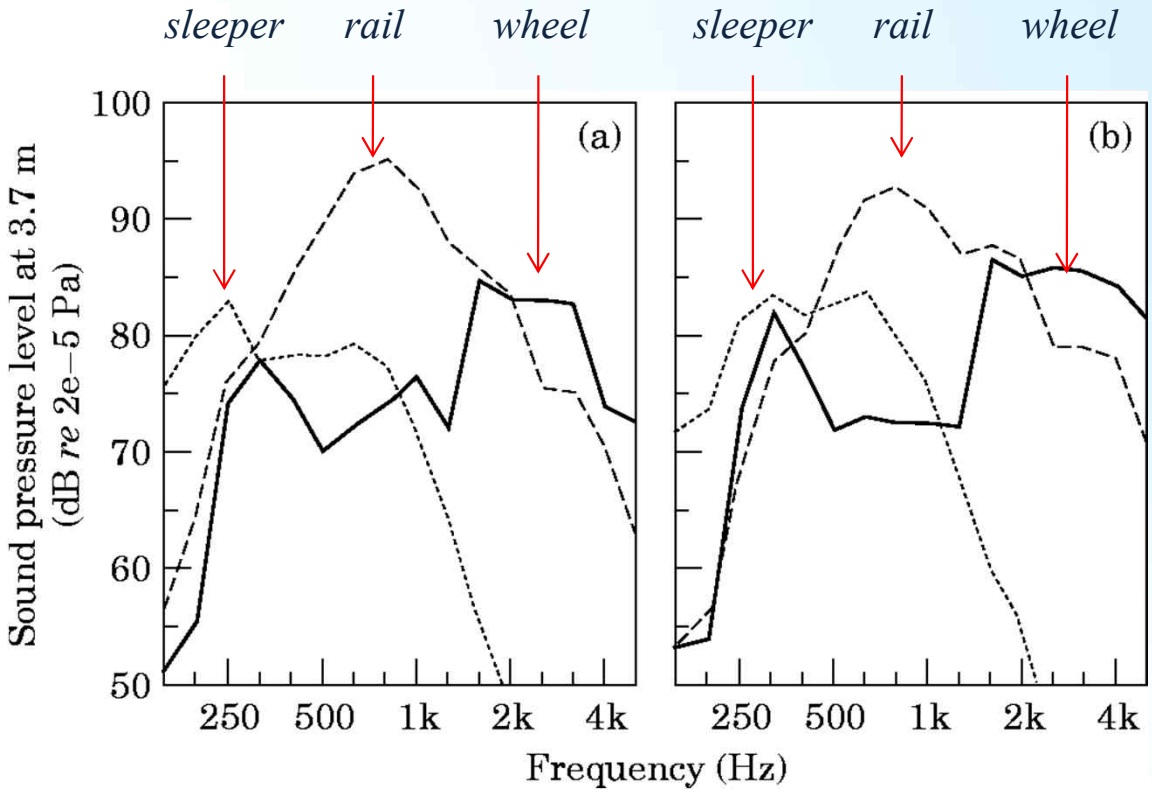
- Flow Noise

Railway Noise Measurement & Analysis

❖ Railway rolling noise





Cited from '*Railway noise and vibration*'
written by D. J. Thompson

Cited from a paper written by D. J. Thompson et al. (JSV, 193, pp.137-147, 1996)

Railway Noise Measurement & Analysis

❖ Railway rolling noise

- ✓ Main sources
  - Sleeper (< about 500 Hz)
  - Rail (about 500 Hz ~1.5 kHz)
  - Wheel (> about 1.5 kHz)

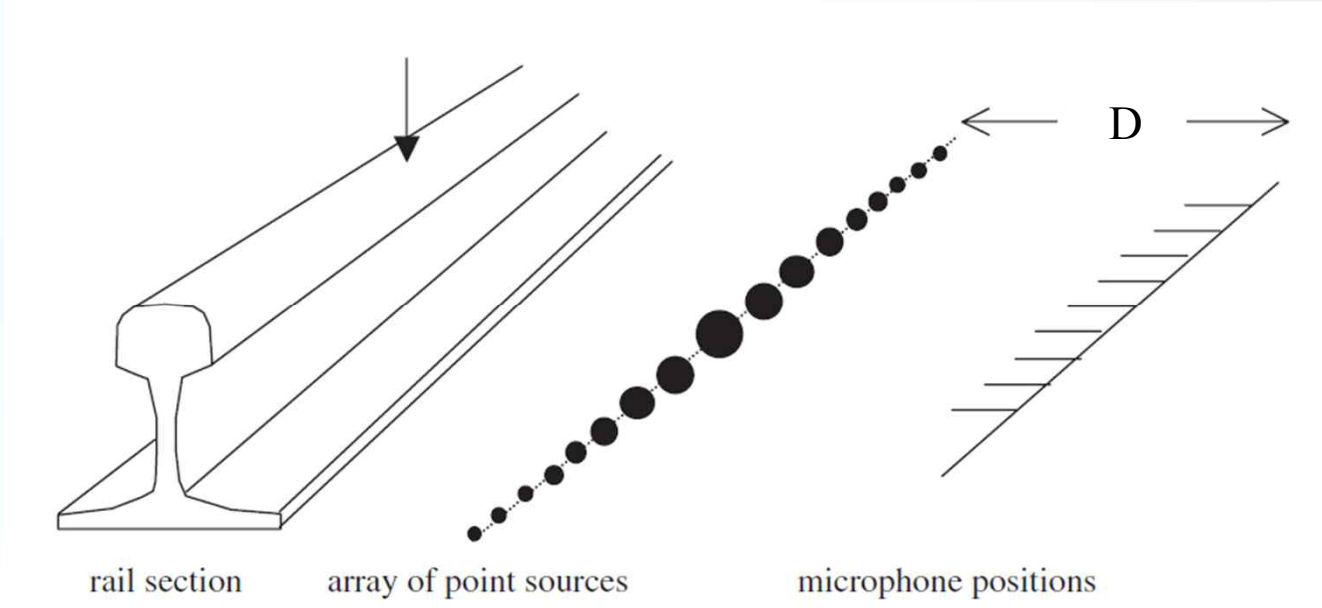
❖ Rolling noise measurements

- ✓ Microphone array is often used to localise sources.
- ✓ However, measured results give less prominence to the rail and more to the wheel.
- ✓ It was reported that sound power measured by microphone array gives at least 10 dB less than the theoretical ones.

❖ Theoretical modeling (cont.)

✓ Rail noise prediction

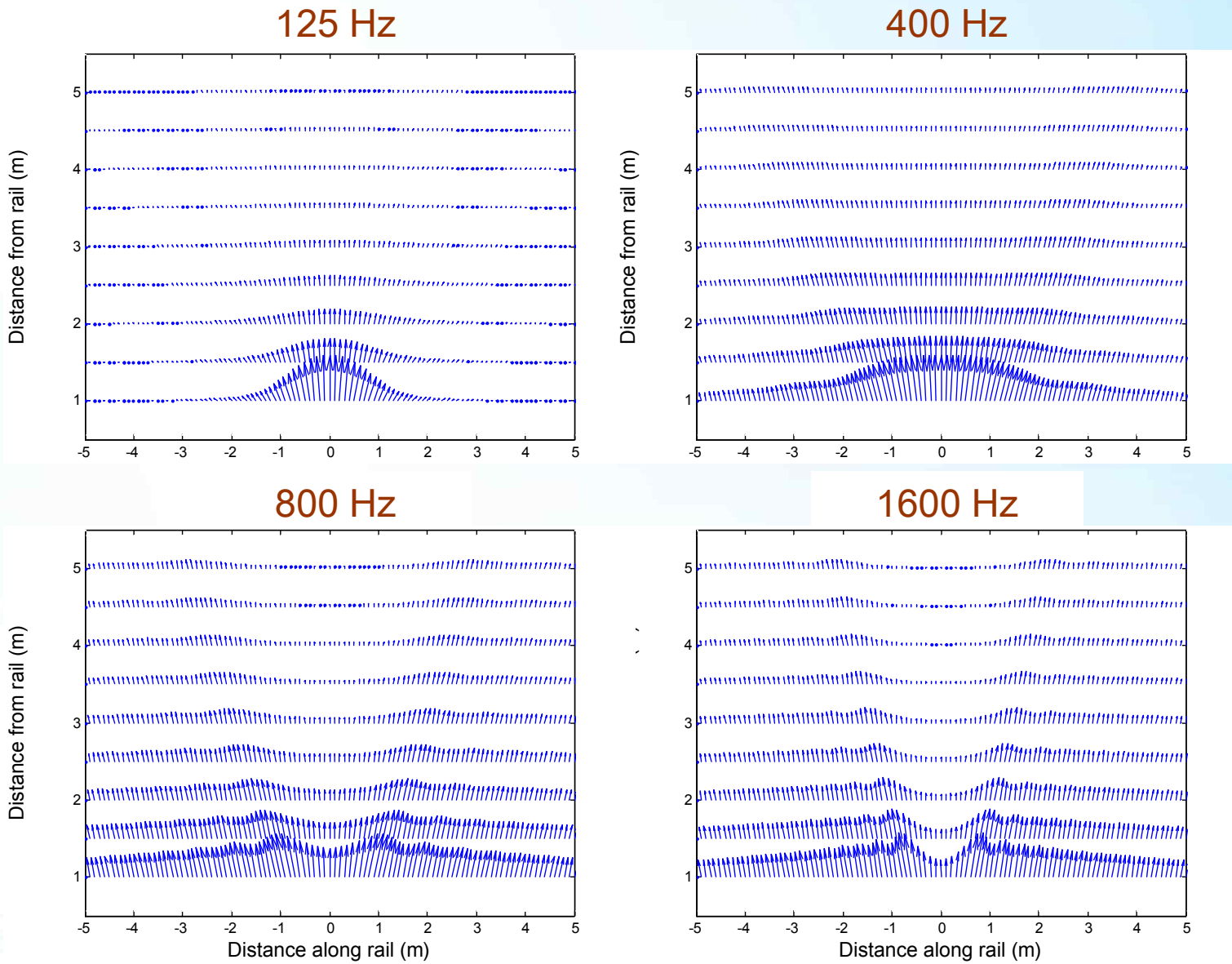
- Series of coherent monopoles along rail



Railway Noise Measurement & Analysis

❖ Rail noise predicted

✓ Stationary load

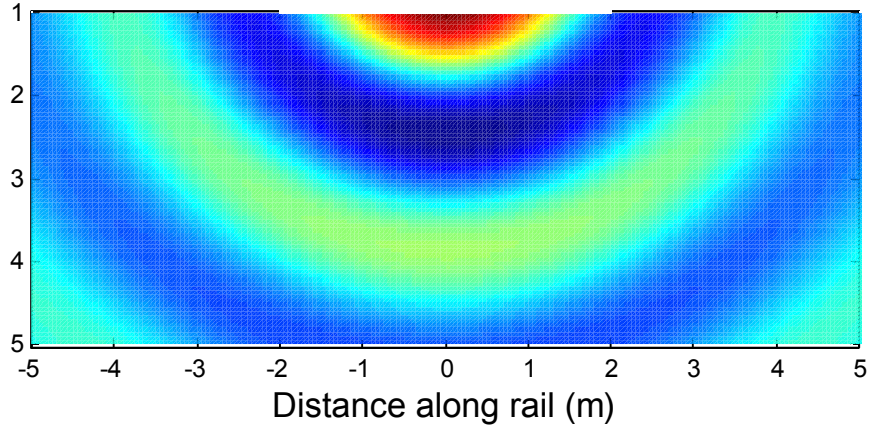


Railway Noise Measurement & Analysis

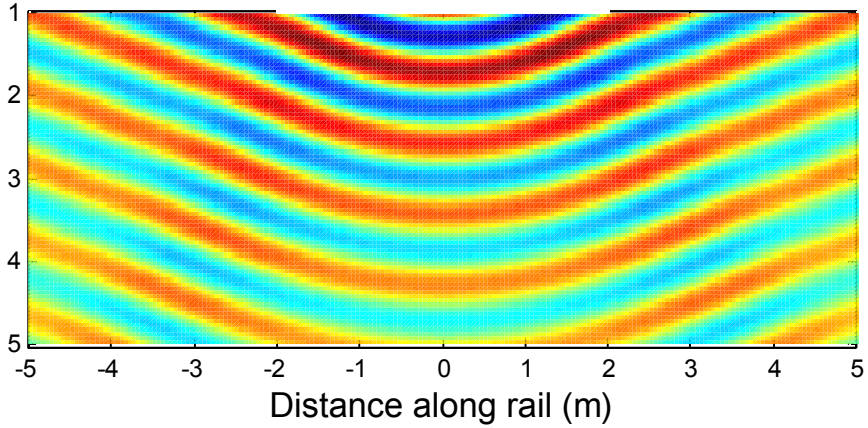
❖ Rail noise predicted

✓ Stationary load

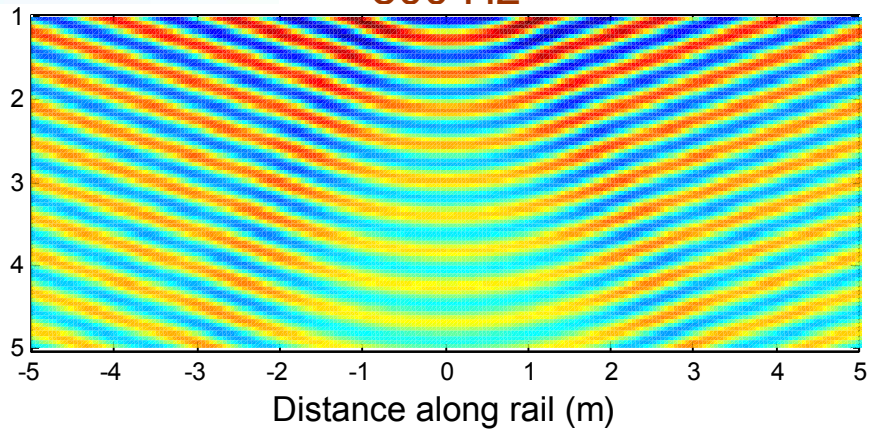
125 Hz



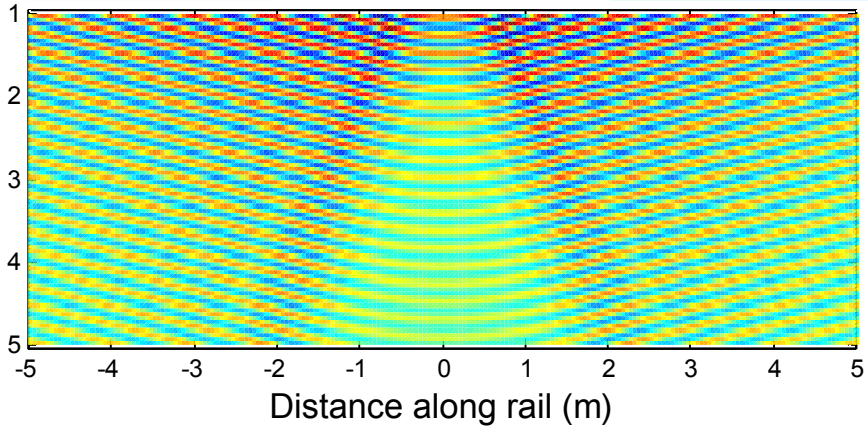
400 Hz



800 Hz



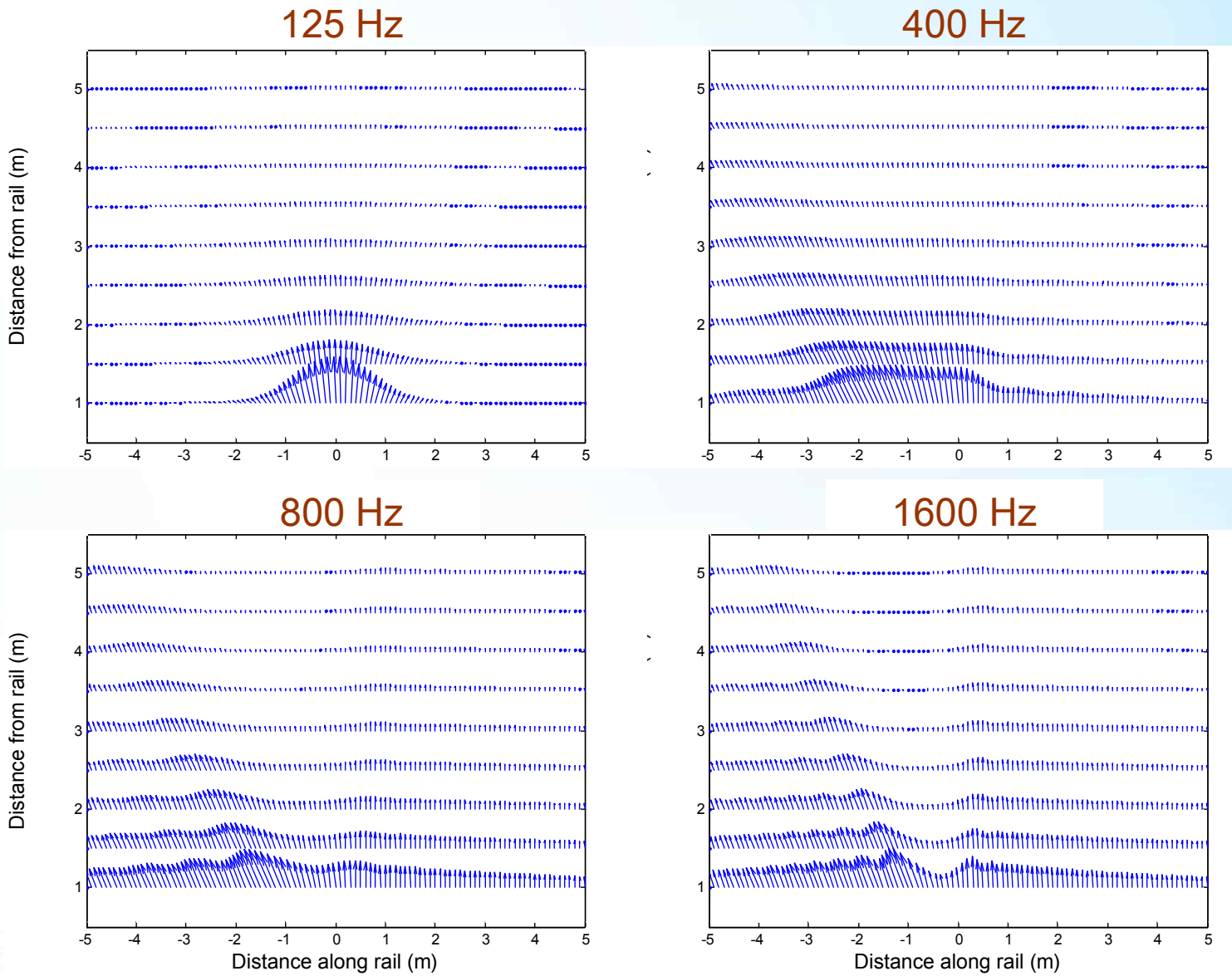
1600 Hz



Railway Noise Measurement & Analysis

❖ Rail noise predicted

✓ Moving load

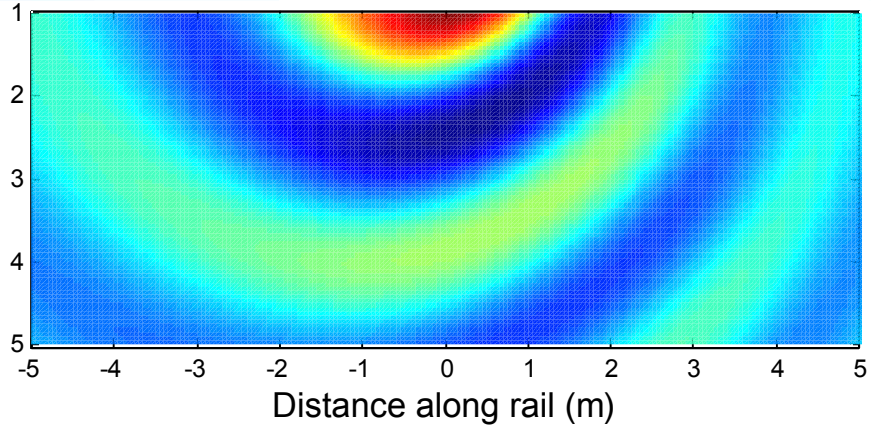


Railway Noise Measurement & Analysis

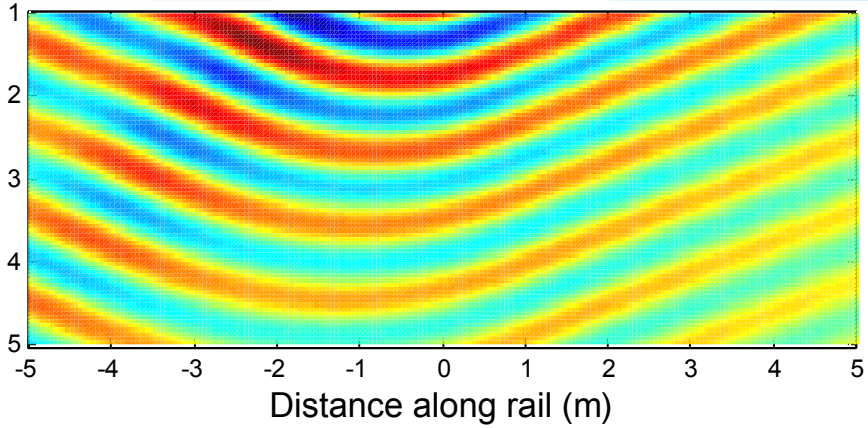
❖ Rail noise predicted

✓ Moving load with V = 111 m/s (400 km/h)

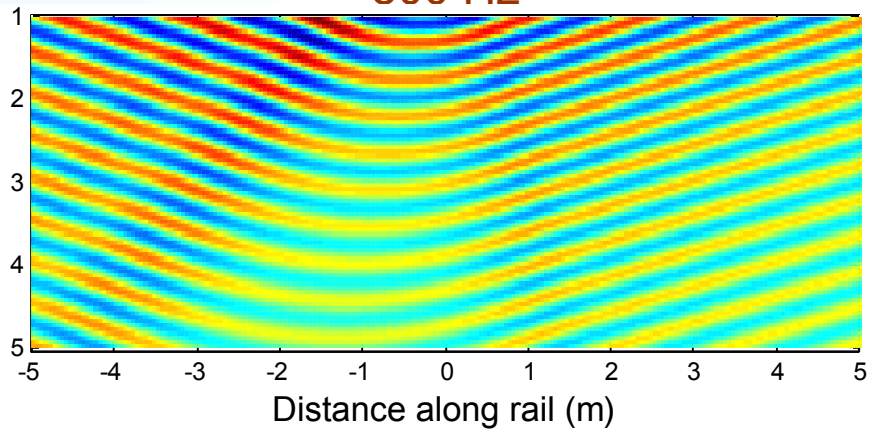
125 Hz



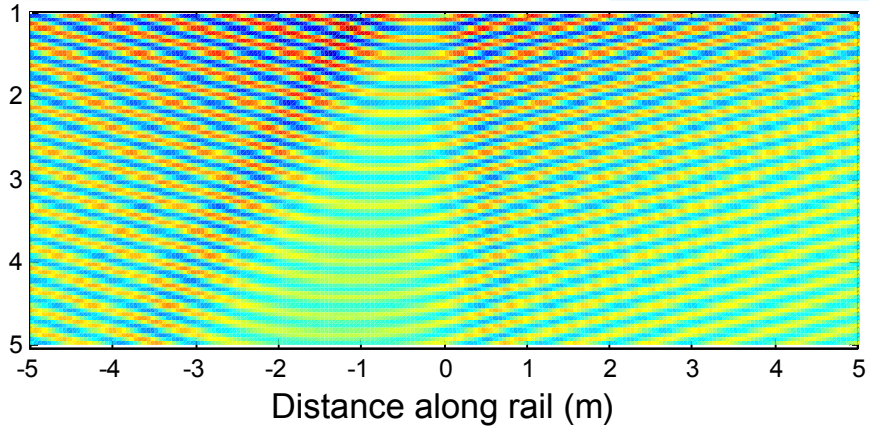
400 Hz



800 Hz



1600 Hz



Railway Noise Measurement & Analysis

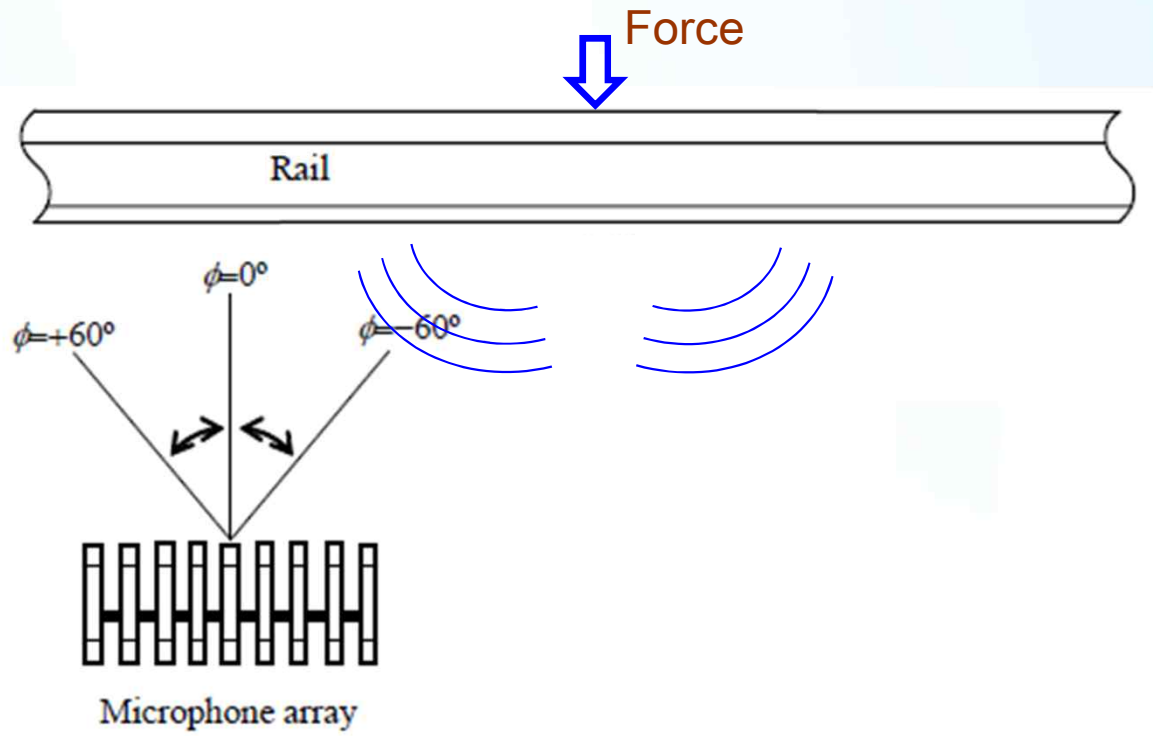
❖ Remarks

- ✓ Rail becomes a line source above 300 Hz
- ✓ For stationary load,
  - Maximum pressure occurs 40° ~20° between 300~3000Hz
  - Phase angle of the rail noise (plane wave) becomes around 20° between 300~3000Hz
- ✓ For a moving load of 400 km/h,
  - Rail noise is radiated more to negative angles
  - Maximum pressure –45° ~ – 30° between 300~3000Hz
  - Phase angle of the rail noise (plane wave) becomes around 20° between 300~3000Hz at negative angles

Railway Noise Measurement & Analysis

❖ Sound pressure from microphone array

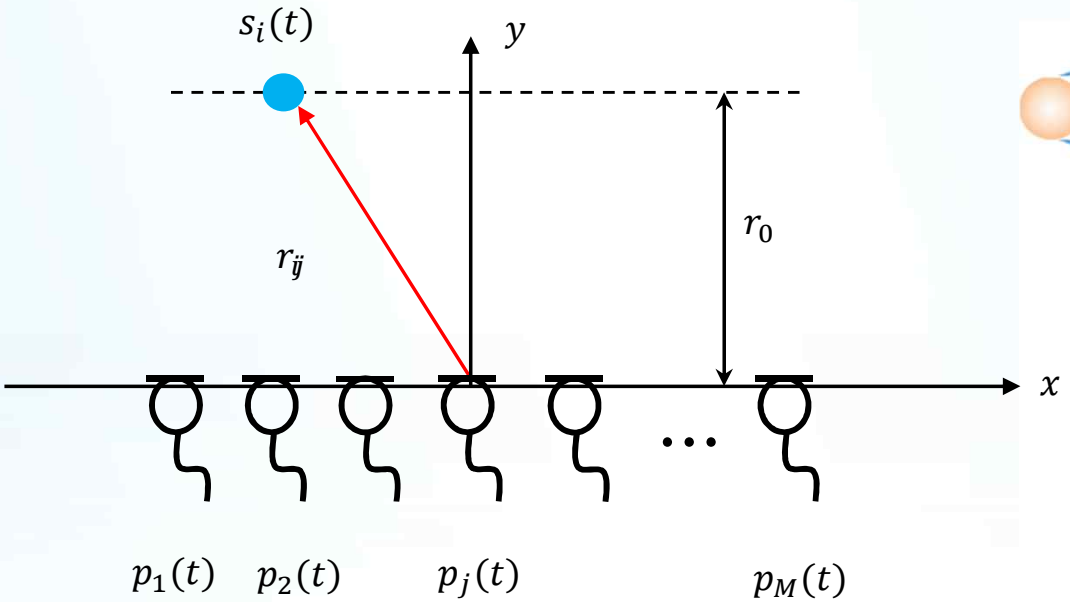
- ✓ Microphone array configuration
  - 17 microphones with 0.11m interval
  - Distance from rail: 5m

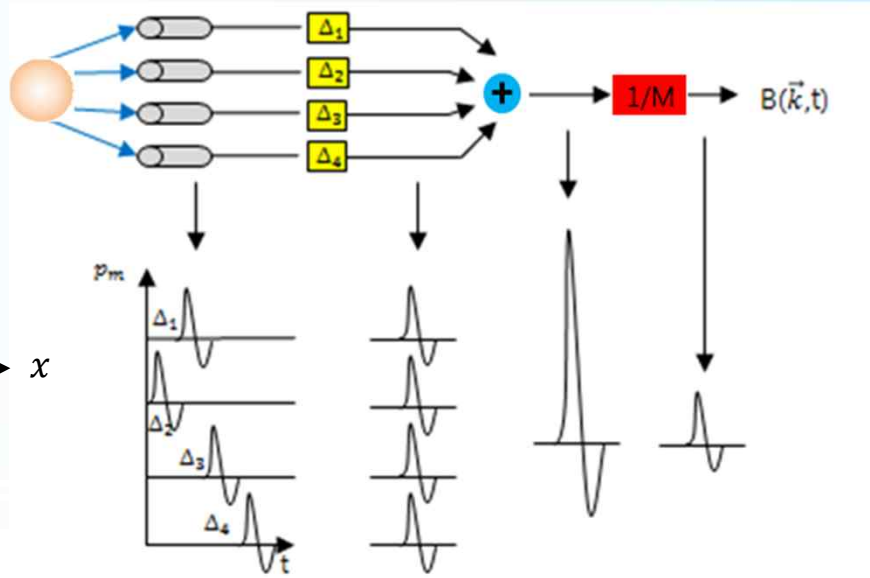


Cited from Kitagawa's PhD thesis

❖ Beam forming of microphone array

✓ Delay and sum in time domain



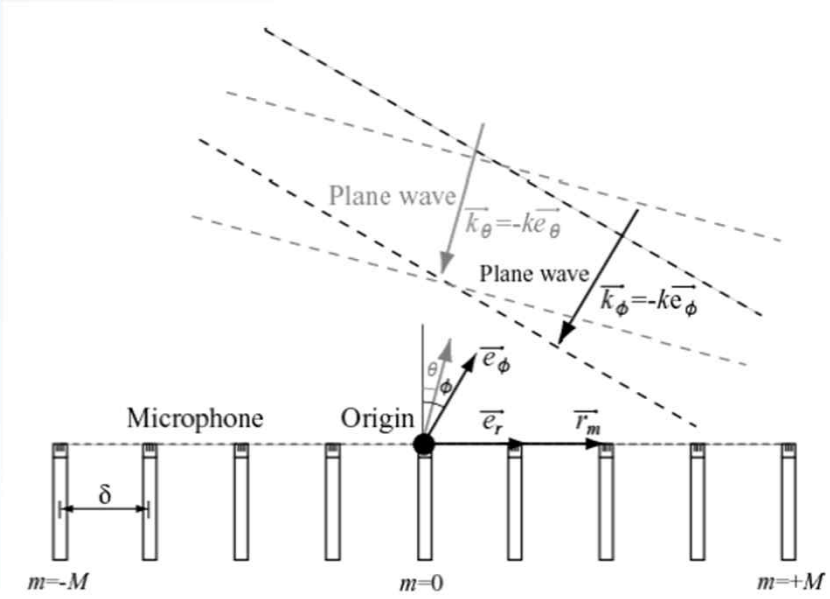


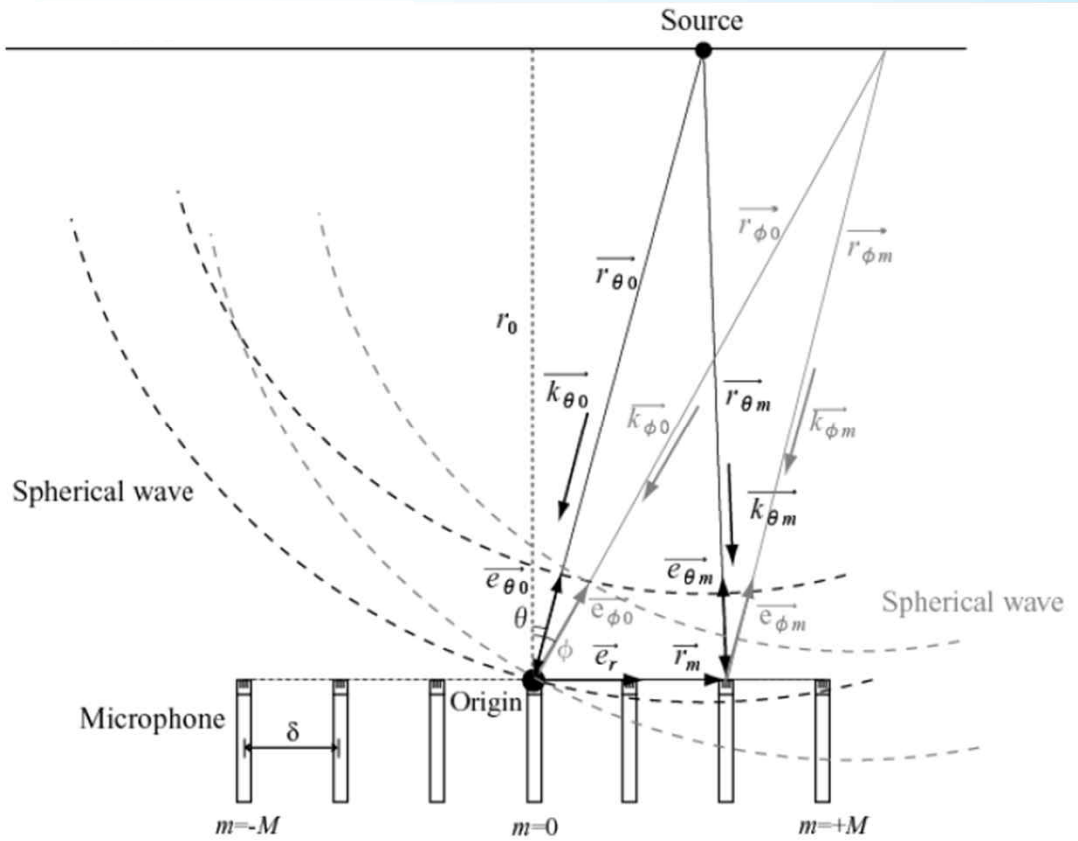
$$s_i(t) \approx \frac{1}{M}\sum_{j=1}^{M} r_{ij}\, p_j\left(t + \frac{r_{ij}}{c}\right) \qquad r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + r_0^2}$$

Railway Noise Measurement & Analysis

❖ Beam forming of microphone array

- ✓ Plane wave or spherical wave models

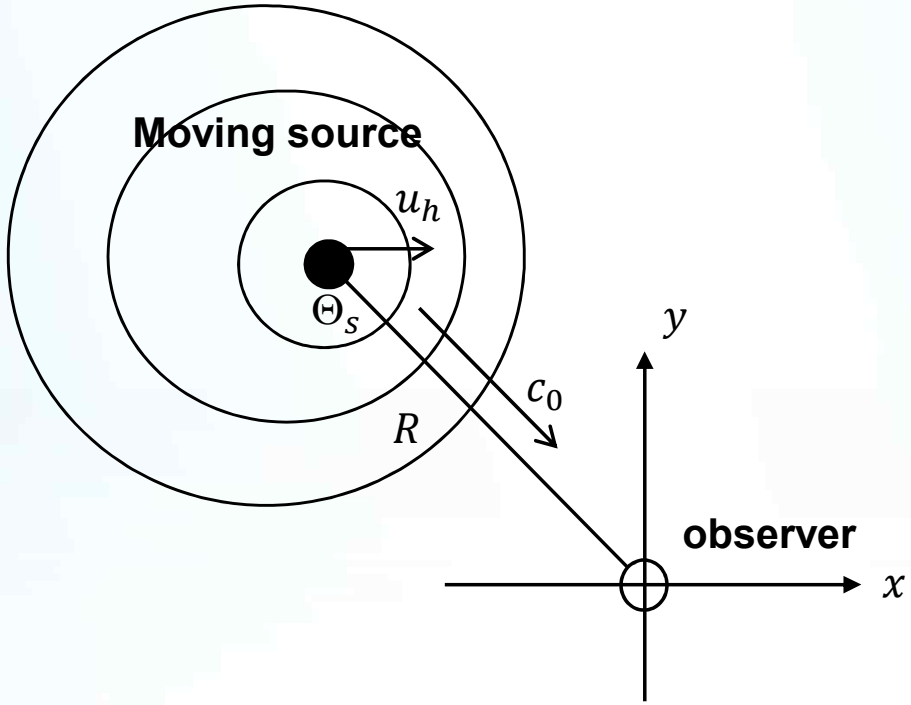




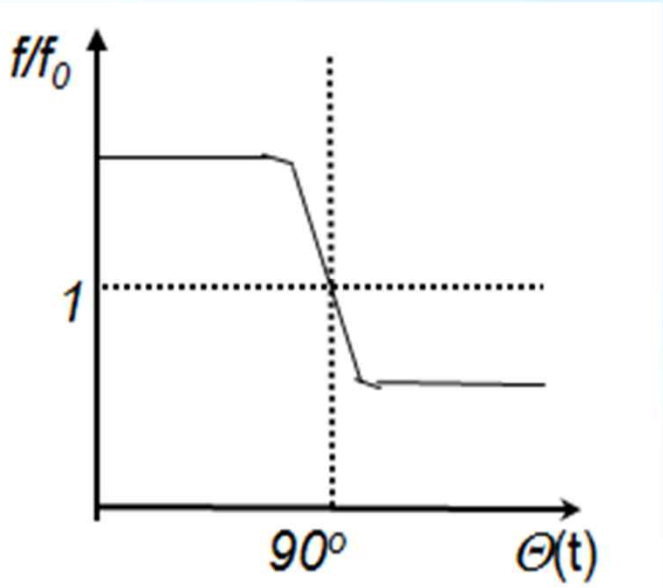
Cited from Kitagawa's PhD thesis

Railway Noise Measurement & Analysis

❖ Doppler effect due to a moving source



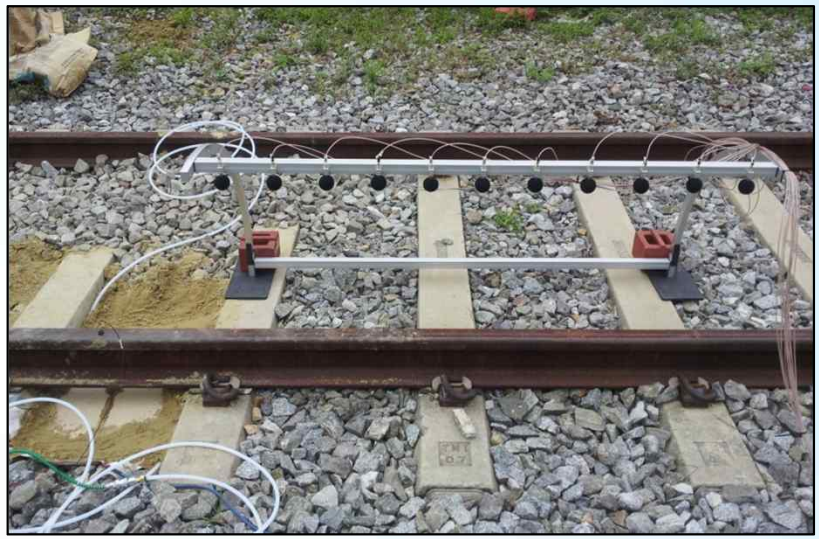
R, Θ_s ~ function of time

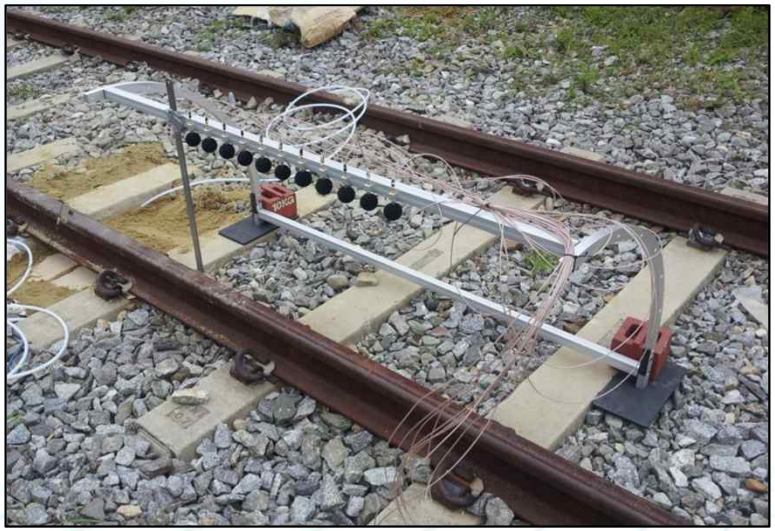


Railway Noise Measurement & Analysis

❖ **Rail noise measurements using a microphone array**

✓ Measurement at a test track



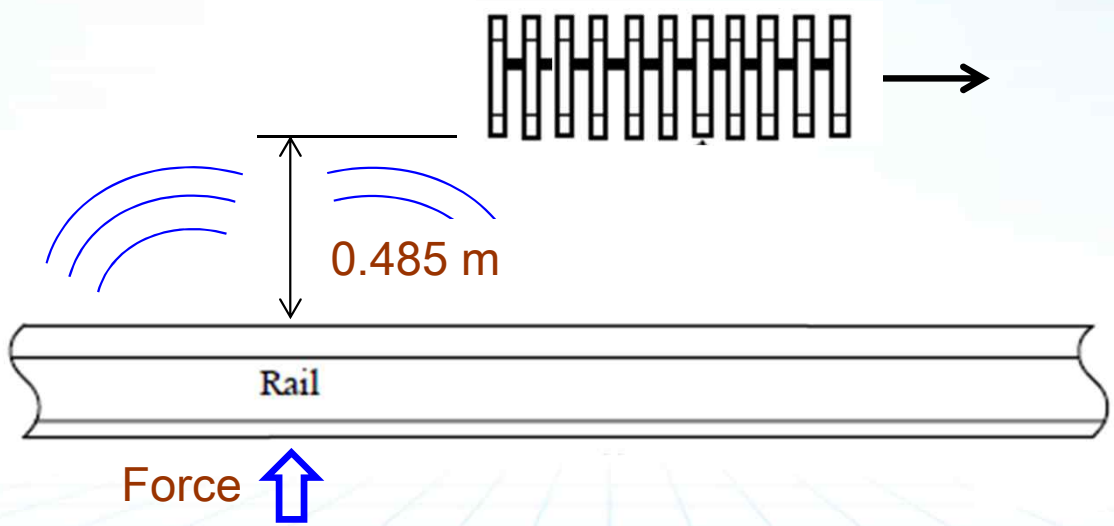


Railway Noise Measurement & Analysis

❖ Measurement setup

✓ Setup

The number of microphones	11
Microphone spacing	0.136 m, 0.068 m
Spatial weighting function	Dolph-Chebyschev
Distance from rail	0.485 m
Excitation frequency	500, 625, 800 Hz (with 0.136 m) 990, 1250, 1580, 2000, 2500 Hz (with 0.068 m)

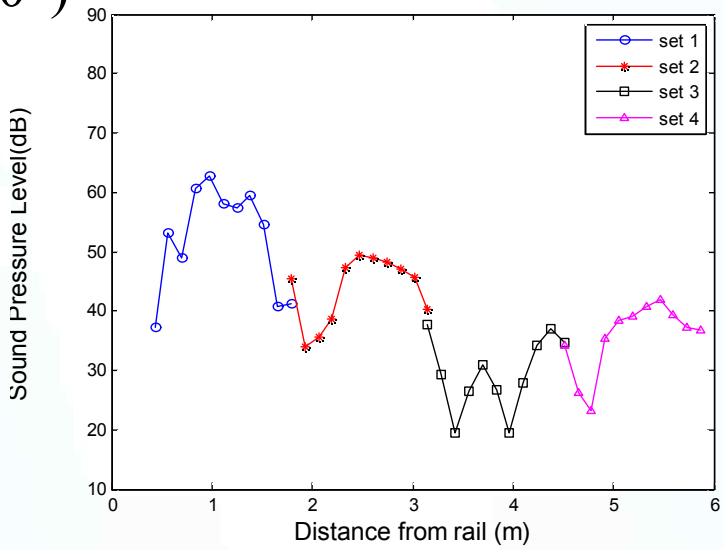


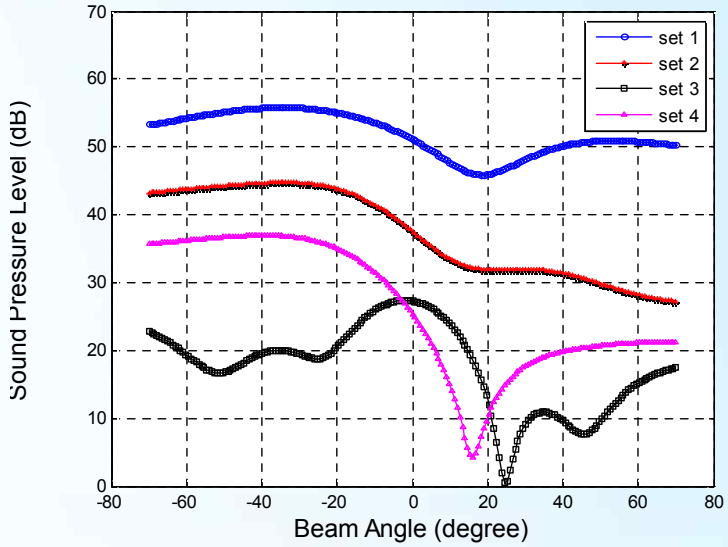
Railway Noise Measurement & Analysis

❖ Pressure distribution and directivity

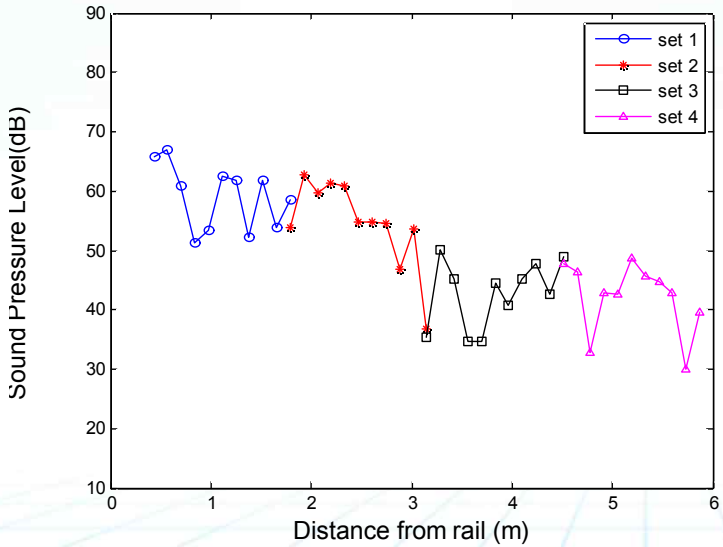
✓ Results (90°)

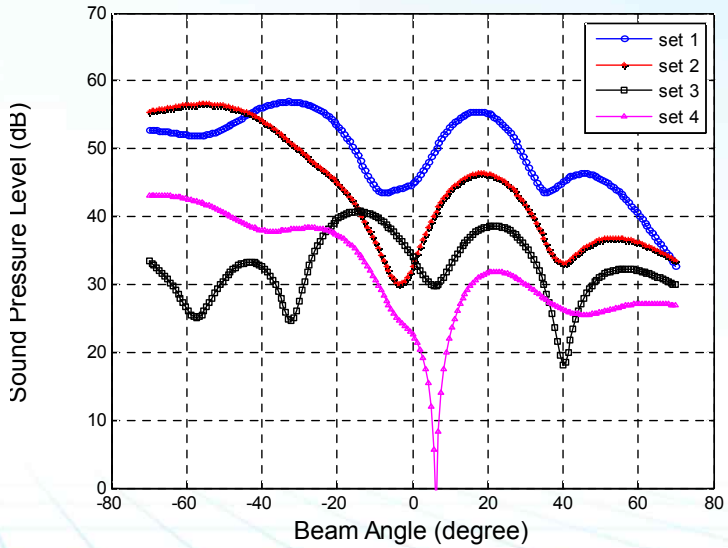
500 Hz





800 Hz





Railway Noise Measurement & Analysis

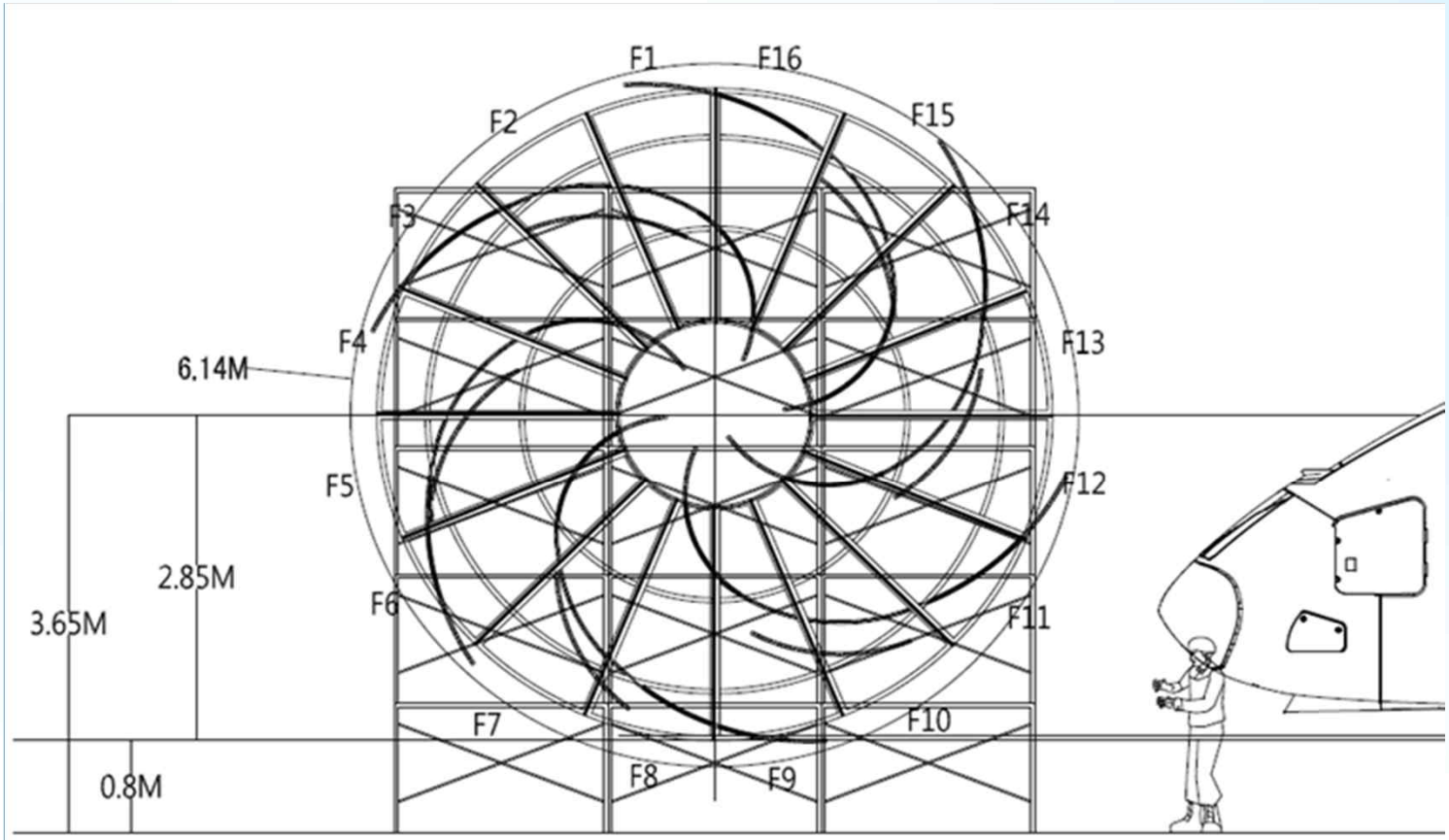
❖ Remarks

- ✓ For a moving load of 400 km/h, the rail noise radiated to the negative angle is about 5 dB louder that that to the positive angle
- ✓ Plane wave vs Spherical wave models
  - Spherical wave model is not good for estimating the phase angle
  - Spherical wave model, however, is not much different from the plane wave model in terms of the noise level
- ✓ Test track measurements were carried out to validate the features of rail noise predicted theoretically
- ✓ However, the measure results do not show consistent results and seem to be less reliable
- ✓ More powerful exciter may be demanded to obtain reliable results from the test track measurement

Sound Images (Microphone Array)

❖ **Measurements on an operational track with HEMU**

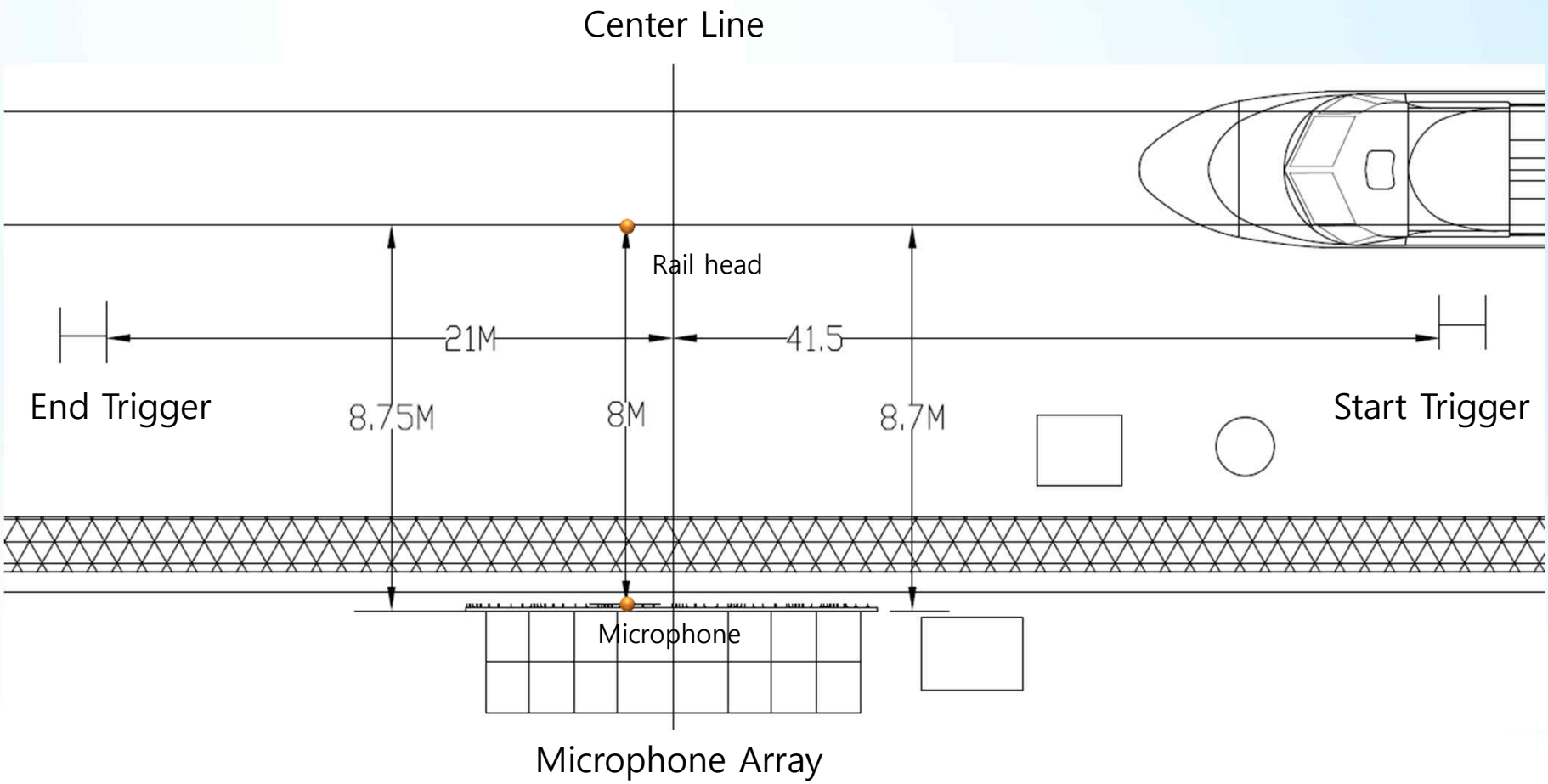
✓ Array microphone configuration



Ground level

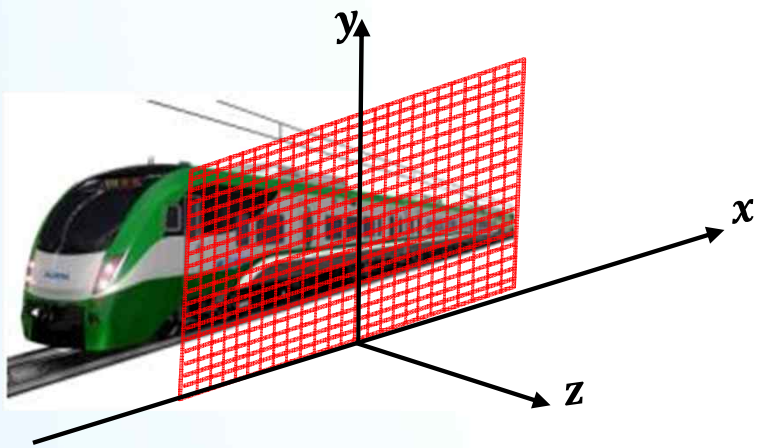
Sound Images (Microphone Array)

❖ Measurement configuration (plane view)

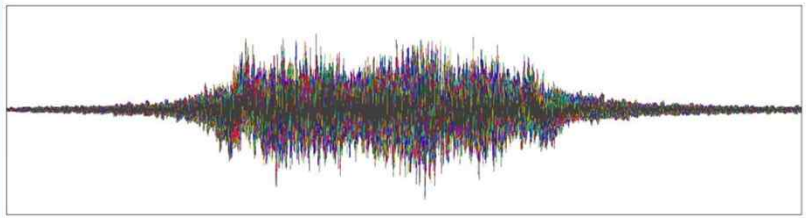


Sound Images (Microphone Array)

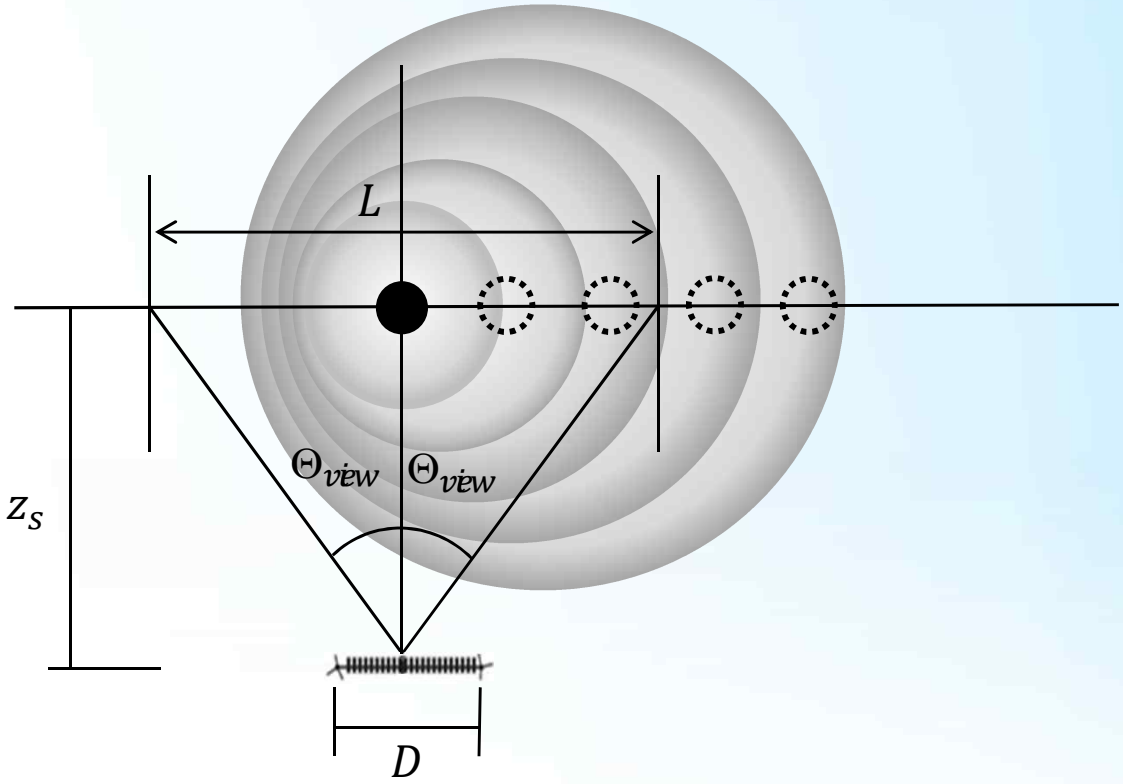
❖ Measurement setup



Virtual source plane & relative coord.



Measured mic. signals (140 ch.)

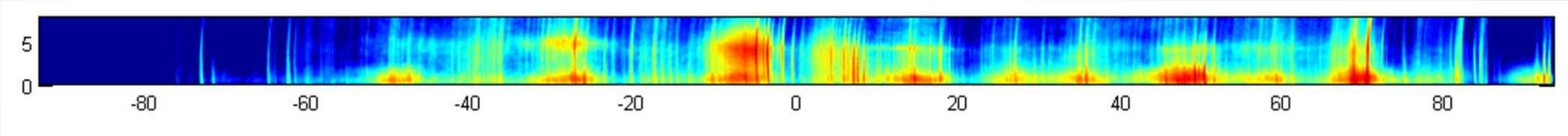


- Positions of mic. array & moving source
- View angle & signal measuring duration, array aperture, …

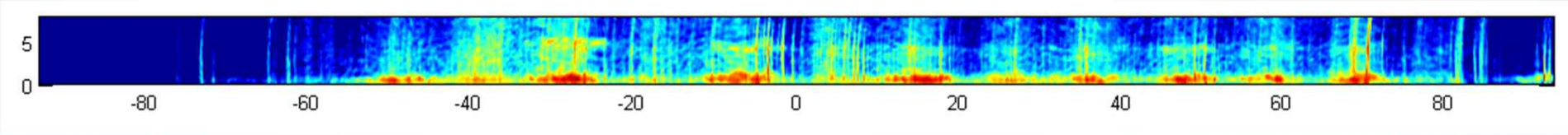
Sound Images (Microphone Array)

❖ Analyzed results

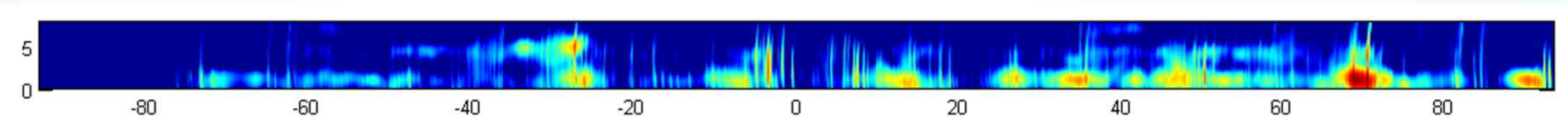
✓ All microphones of view angle 44° (train passage 15.5 m)



(a) Reconstructed source image (whole freq. range)



(b) Reconstructed source image (freq. range: 800 ~ 1500 Hz)

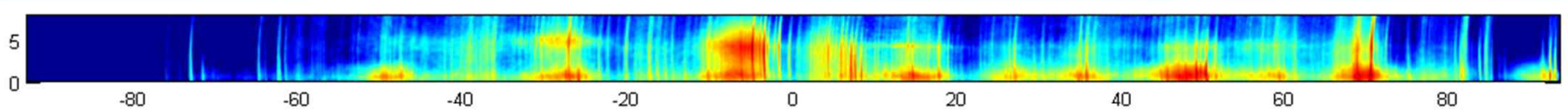


(c) Reconstructed source image (freq. range: 200 ~ 400 Hz)

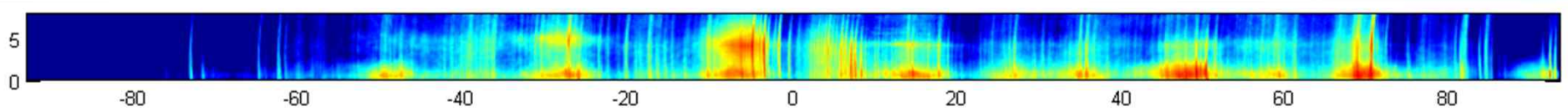
Sound Images (Microphone Array)

❖ Analyzed results

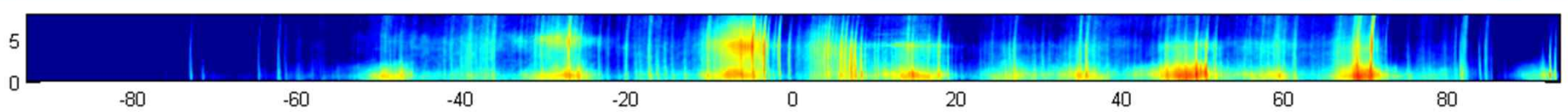
✓ Whole freq. range, view angle 44° (train passage 15.5 m)



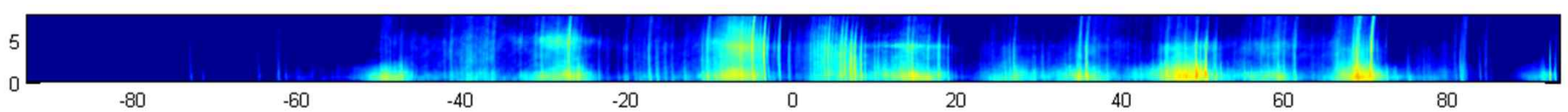
(a) Reconstructed source image (use of all (140) microphones)



(b) Reconstructed source image (use of 128 microphones)



(c) Reconstructed source image (use of 116 microphones)

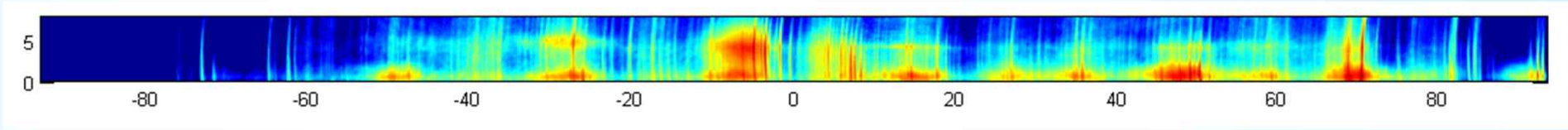


(d) Reconstructed source image (use of 104 microphones)

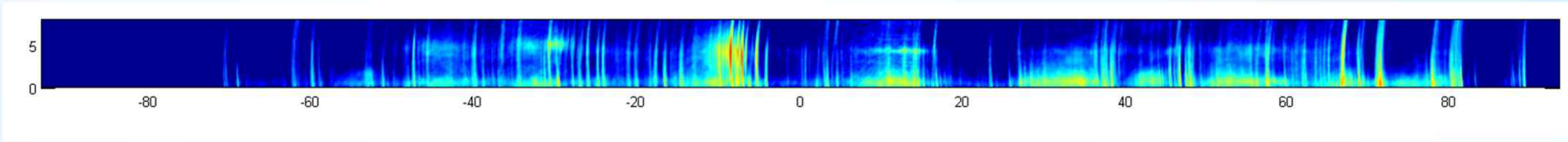
Sound Images (Microphone Array)

❖ Analyzed results

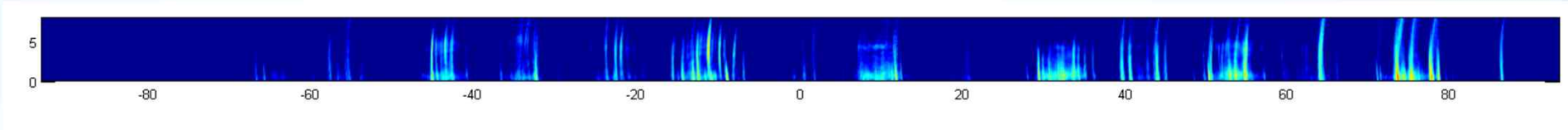
✓ Whole freq. range, all microphones



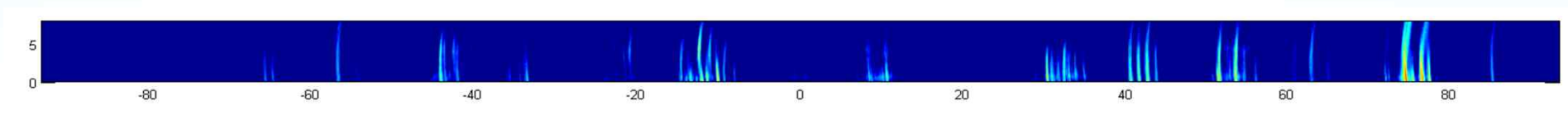
(a) View angle : 44°



(b) View angle : 30°



(c) View angle : 15°



(d) View angle : 7.5°

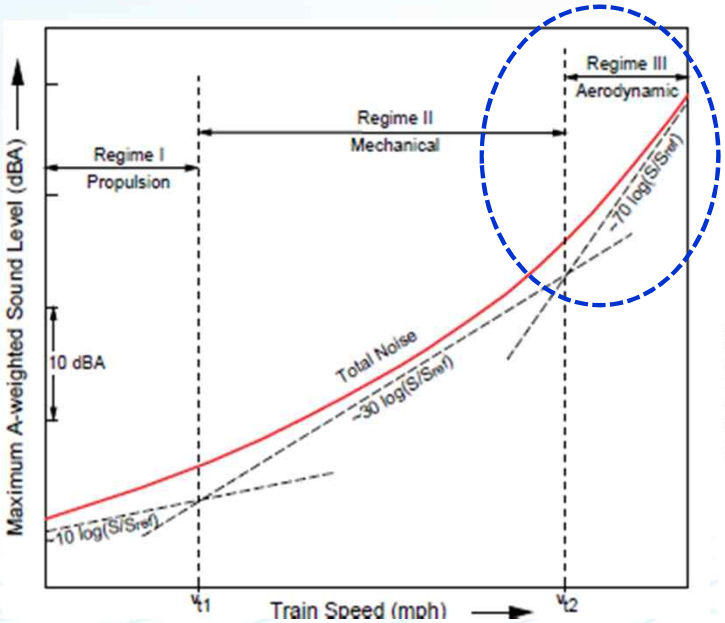
Sound Images (Microphone Array)

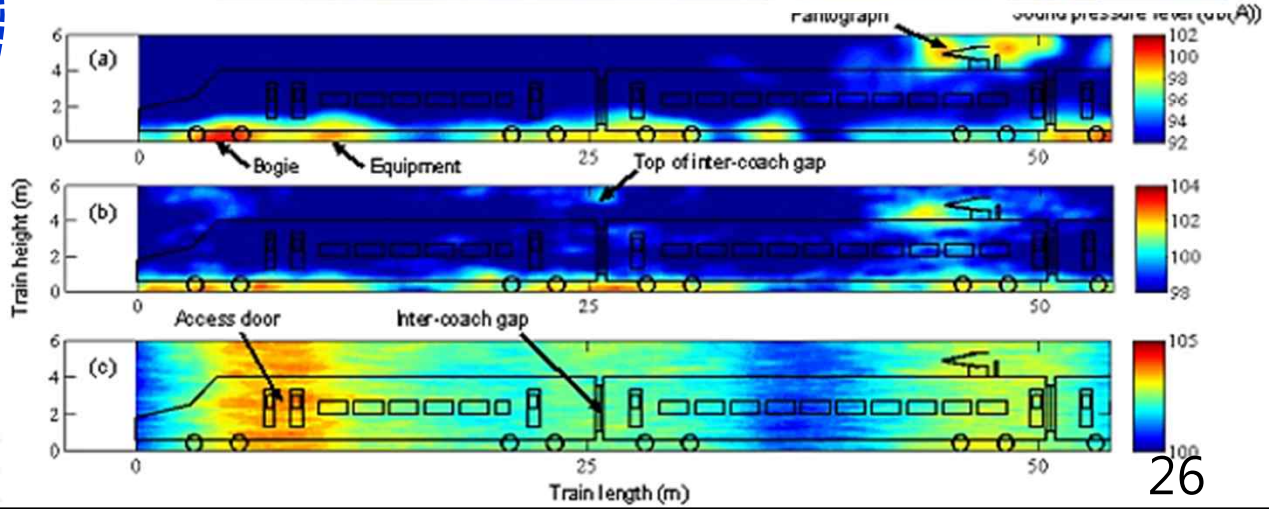
❖ Remarks

- ✓ Pass-by noise of HEMU measured on an operational track were analysed
- ✓ Data measured by a spiral two dimensional array with 140 microphones were investigated varying the view angles and array size
- ✓ It was found that the rail is displayed as a noise source in the scanned image
- ✓ However, the expected features of the rail noise predicted theoretically were not clearly shown in this measured data analysis
- ✓ More systematic and severe analysis for this measured data is required to identify the key parameters and configurations to measure rail noise with array microphones

Flow Noise Measurement & Analysis

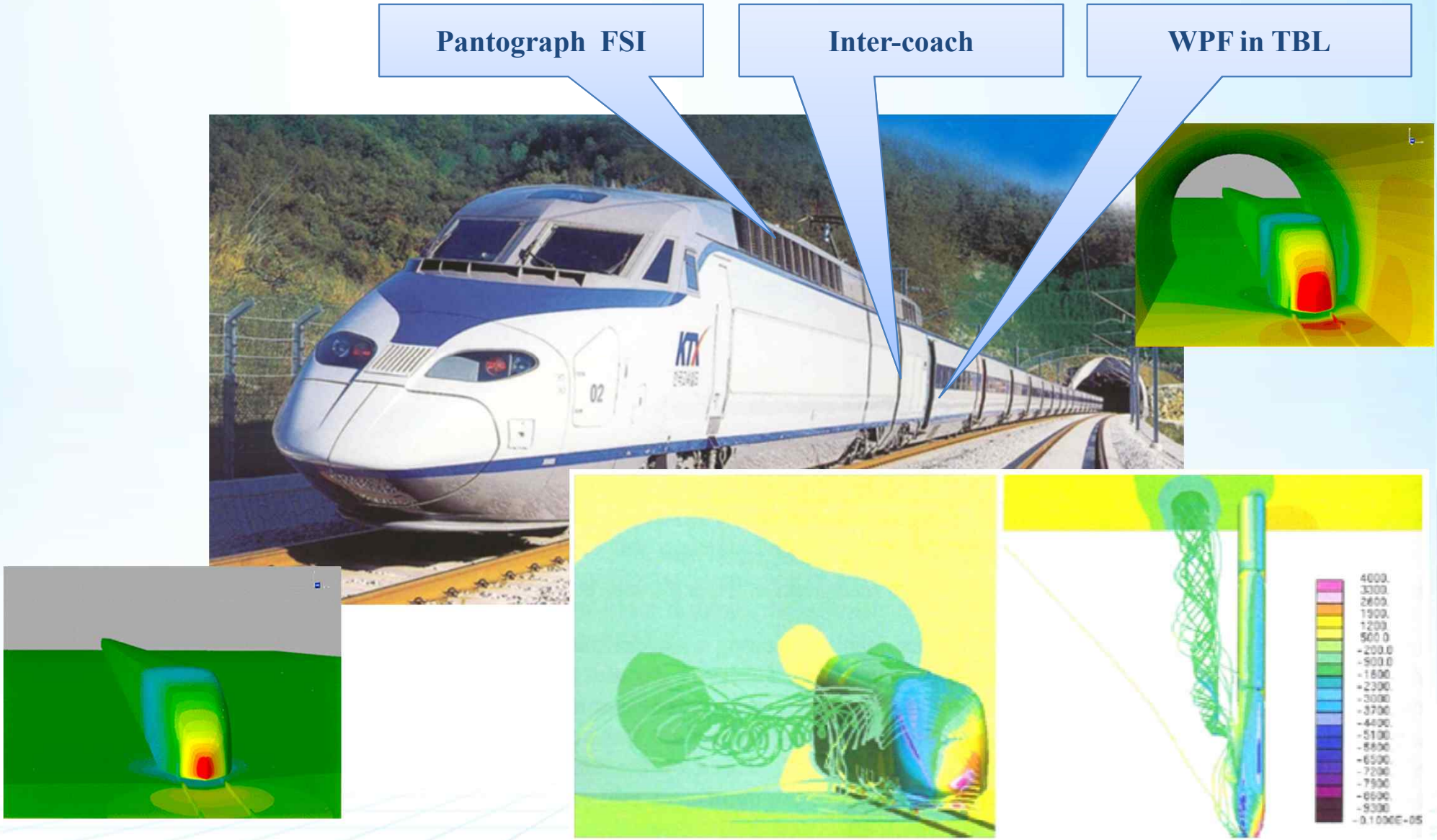
❖ Flow induced noise in high-speed train





Flow Noise Measurement & Analysis

❖ Flow Noise Sources

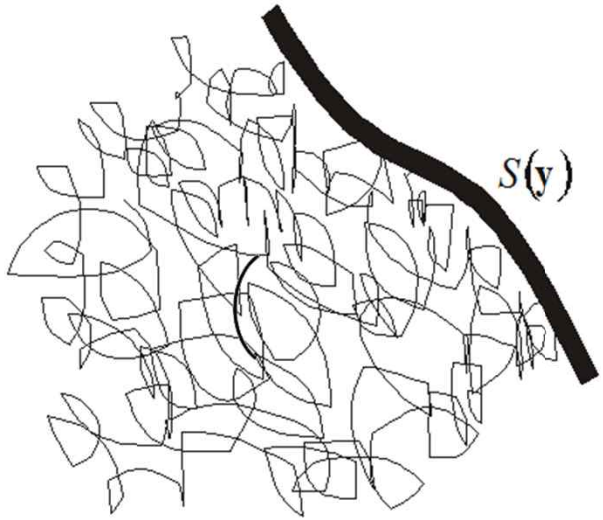


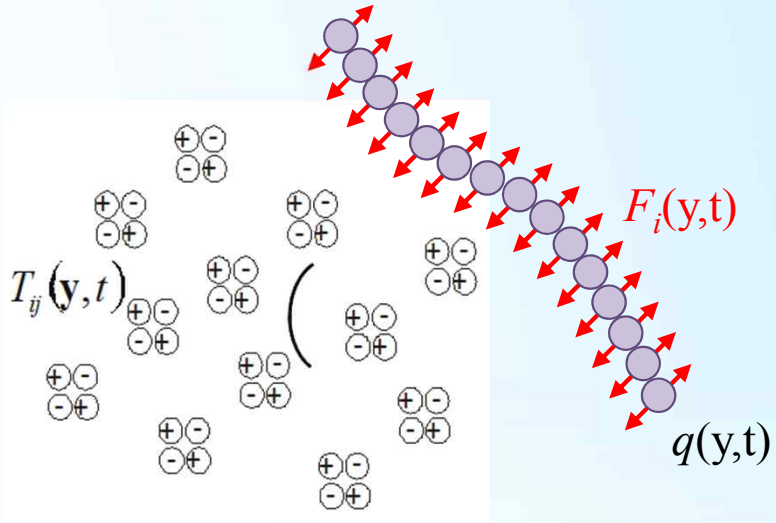
Flow Noise Measurement & Analysis

❖ Acoustic Analogy

- ✓ **For noise generated by flow over a surface**

Observer





$$\frac{\partial^2 p}{\partial^2 x_i} - \frac{\partial^2 p}{\partial^2 t} = q + \frac{\partial F_i}{\partial x_i} + \frac{\partial^2 T_{ij}}{\partial x_i x_j}$$

Curle's acoustic analogy
(Proc Roy Soc, A231, 1955)

Flow Noise Measurement & Analysis

❖ Complete Governing Equations

Theoretically,

Fluid Flow

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathrm{v}) = 0$$

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho vv - \tau) = f^B$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho \mathrm{v} E - \tau \cdot \mathrm{v} + \mathrm{q}) = \mathrm{f}^{\mathrm{B}} \cdot \mathrm{v} + \mathrm{q}^{\mathrm{B}}$$

$$\rho = \rho(p, \theta) \quad \text{and} \quad e = e(p, \theta)$$

+

Structure

$$\mu \nabla^2 u_i + (\lambda + \mu) \frac{\partial \vartheta}{\partial x_i} + F_i = \rho \ddot{u}$$

+

Compatibility equations

Numerically,

FVM

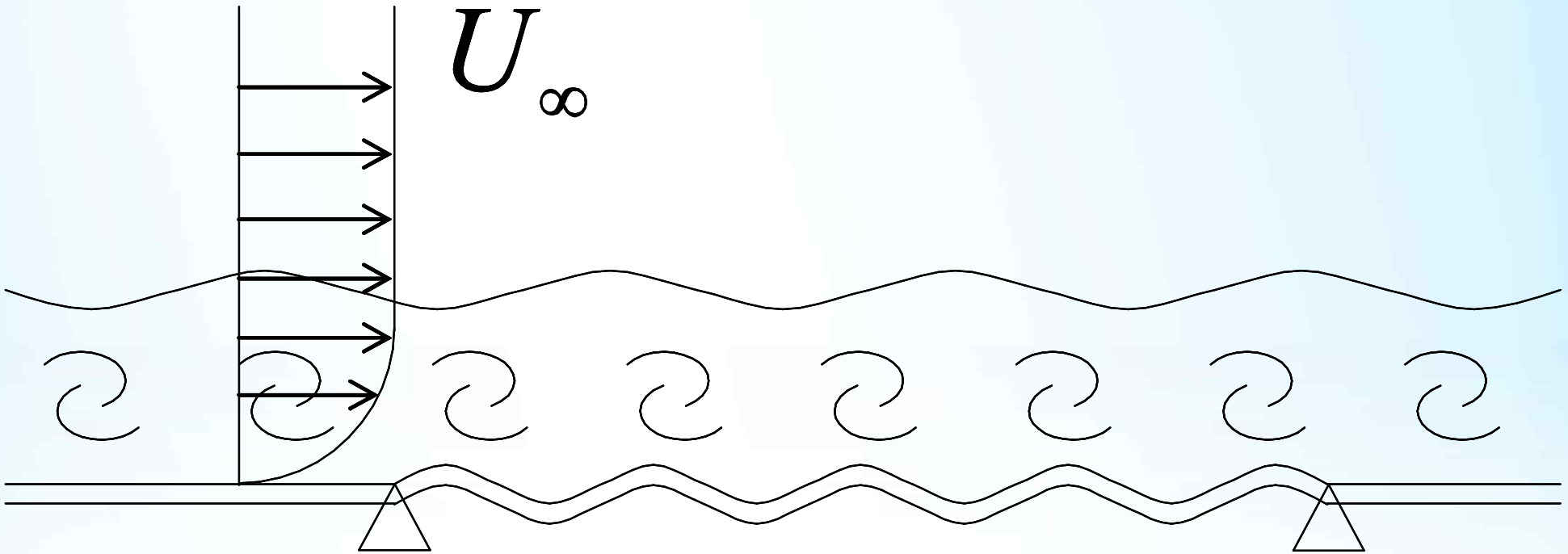
$$M \; {}^{t+\Delta t}\ddot{U}^{(i)} + C \; {}^{t+\Delta t}\dot{U}^{(i)} + {}^{t}K\Delta U^{(i)} = {}^{t+\Delta t}R - {}^{t}F^{(i-1)}$$

FEM

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} - \mathbf{G}^T \mathbf{A}\mathbf{p}$$

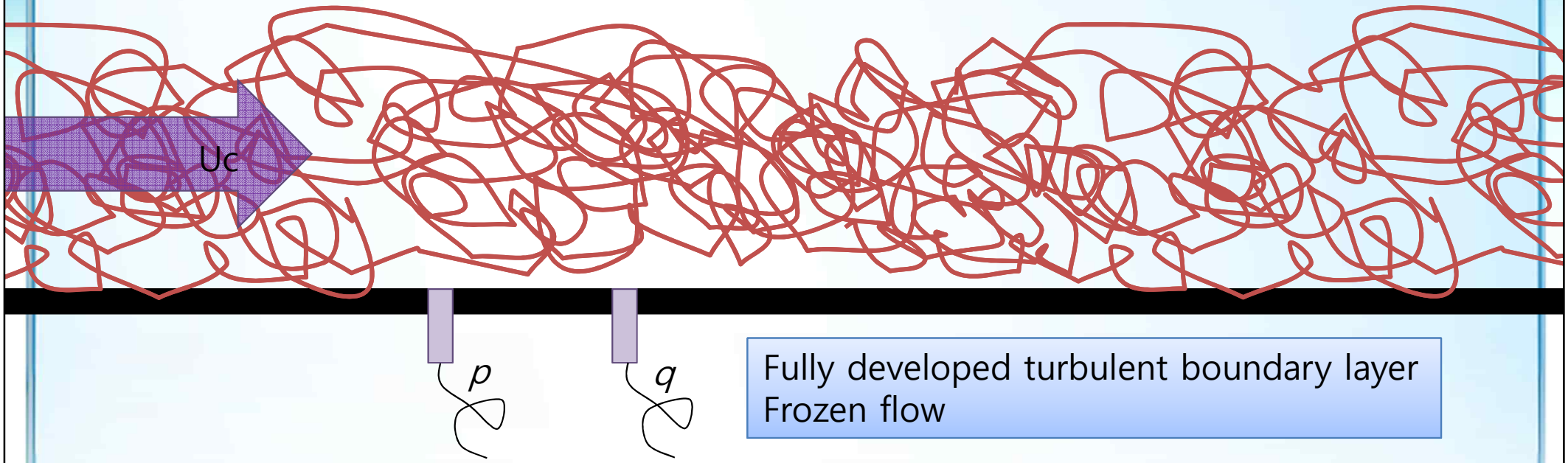
Flow Noise Measurement & Analysis

❖ **Simple Example**



Flow Noise Measurement & Analysis

❖ Flow noise source model: Corcos Model



Fully developed turbulent boundary layer
Frozen flow

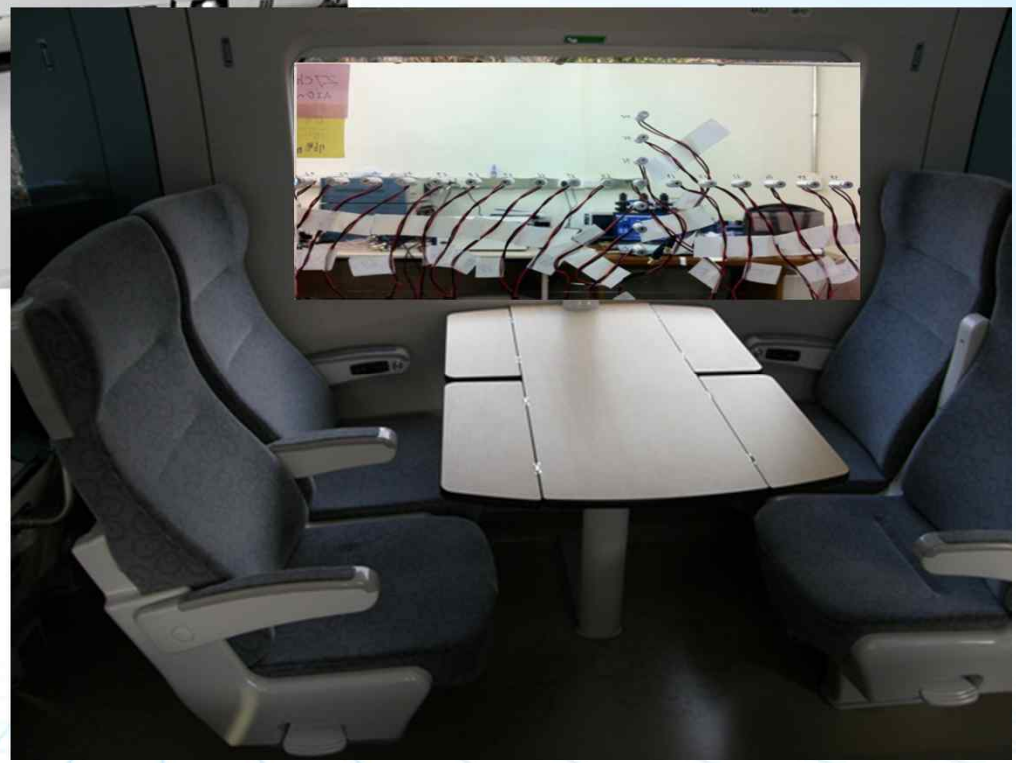
$$C_{pq}(\gamma_x, \gamma_y; \omega) = C_{pp}(\omega) A(\omega\gamma_x / U_c) B(\omega\gamma_y / U_c) e^{-j(\omega\gamma_x / U_c)}$$

$$A = \exp(-\alpha|\omega\gamma_x / U_C|)$$

$$B = \exp(-\beta|\omega\gamma_y / U_C|)$$

Flow Noise Measurement & Analysis

❖ **Measurement on the running train (planning)**

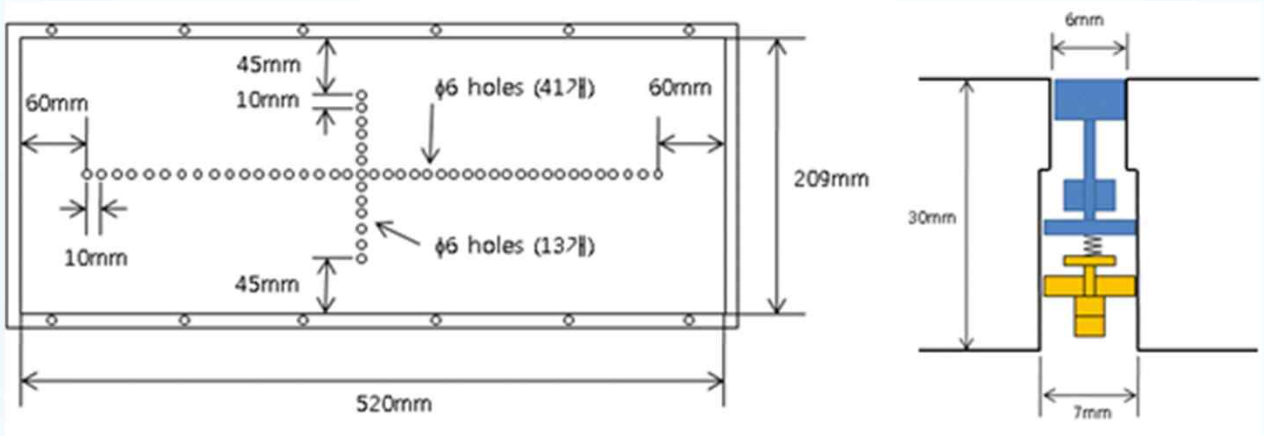


Flow Noise Measurement & Analysis

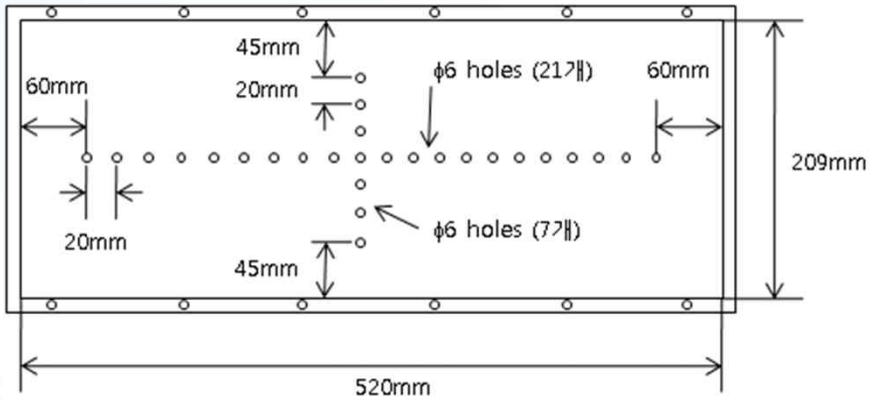
❖ Measurement setup

✓ Design of Wall plate

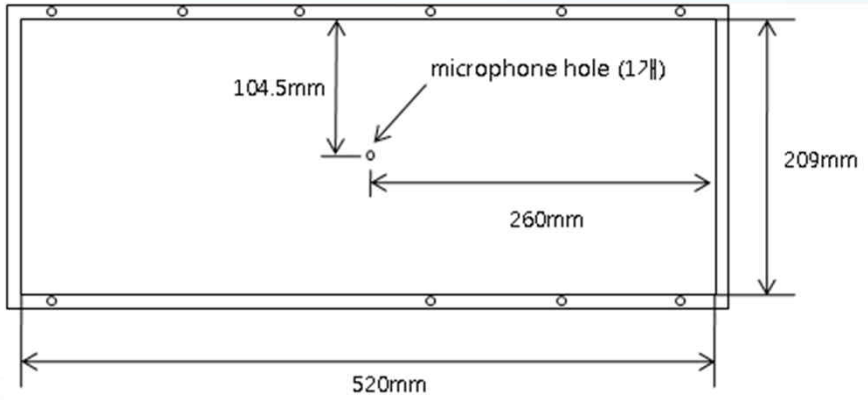
Considering point pressure, spatial correlation, damping, etc.



(a) Flush mounted mic. array (horizontal 41 & vertical 13 mics.)



(b) Flush mounted mic. array (horizontal 21 & vertical 7 mics.)

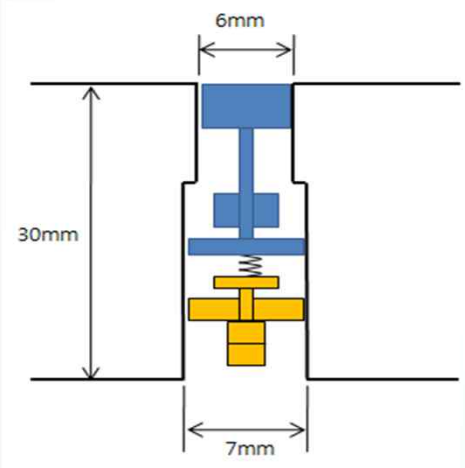


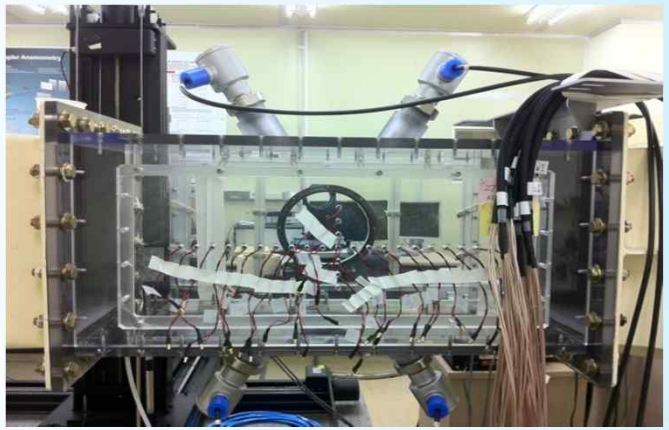
(c) A mic. at the center

Flow Noise Measurement & Analysis

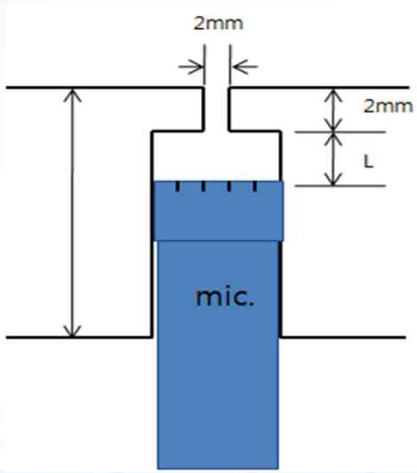
❖ Flow Noise Measurement by Microphones

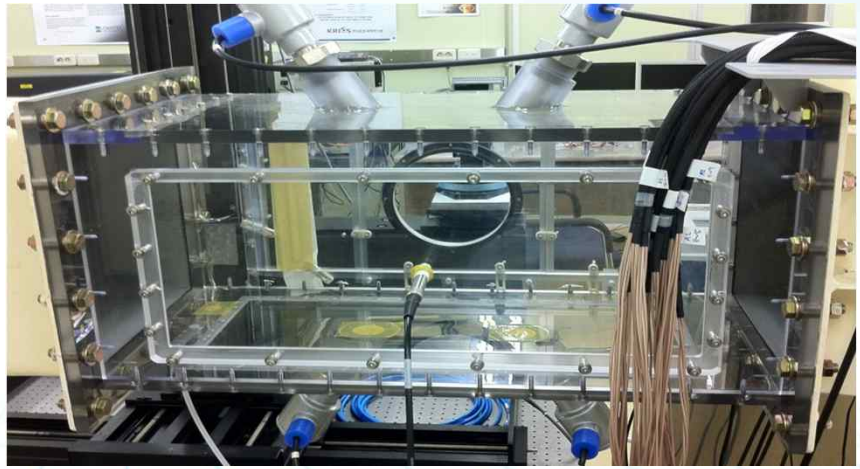
✓ Flush mounting





✓ Pinhole mounting

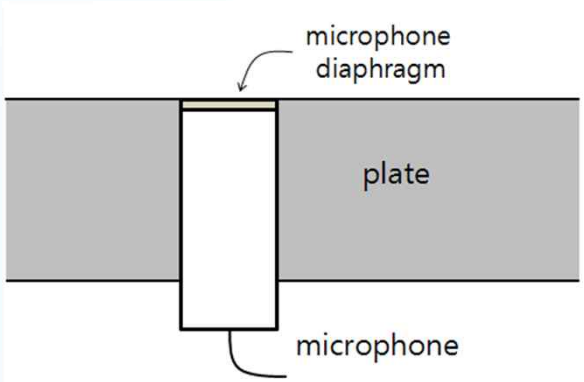


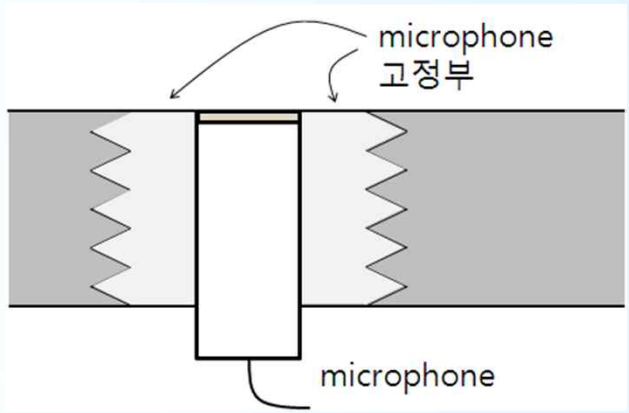


Flow Noise Measurement & Analysis

❖ Microphones on the wall

✓ Flush mounting

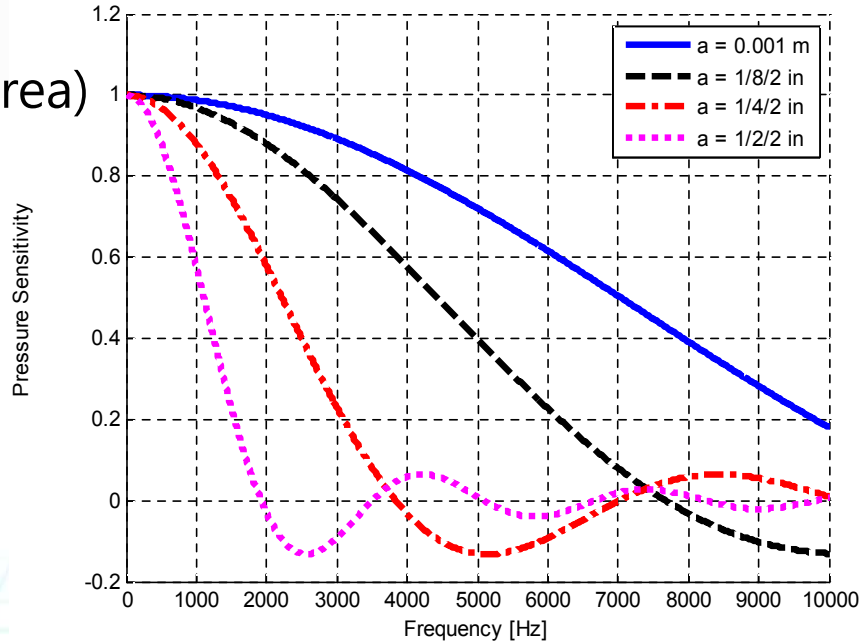




- Sensitivity of microphone (circ. area)

$$s(k_x, k_y) = \frac{2J_1(ka)}{ka}$$

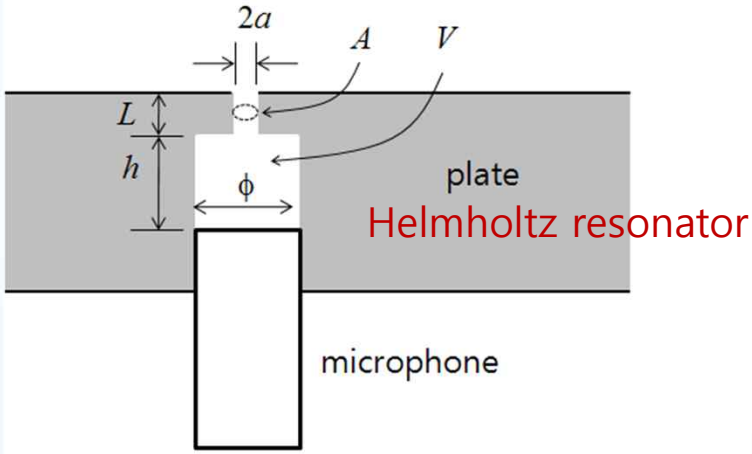
Mic. Sensitivity relative to radius of diaphragm →

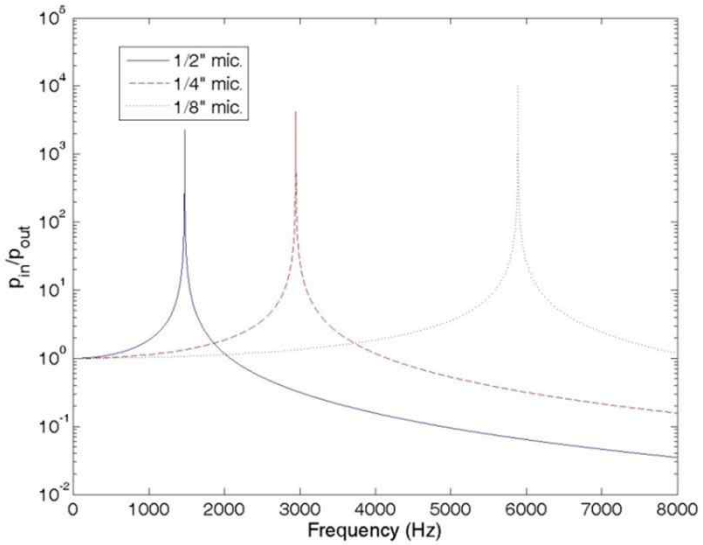


Flow Noise Measurement & Analysis

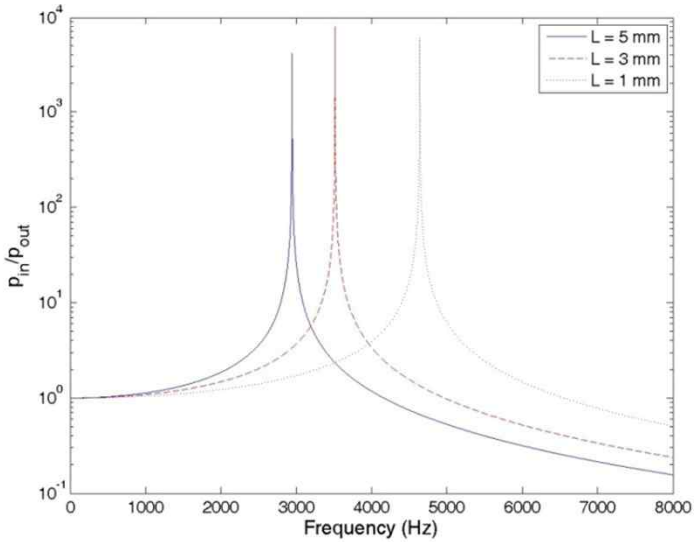
❖ Microphones on the wall

✓ Pinhole mounting

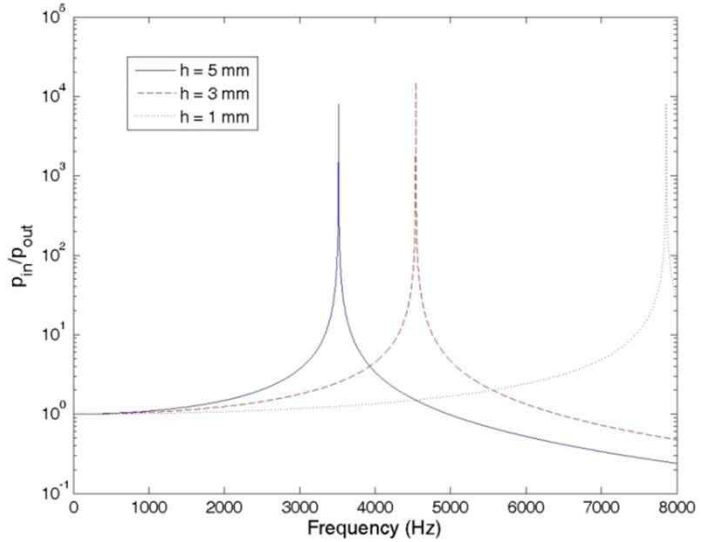




Res. freq. of pin hole w.r.t. the radius of mic.
a =11mm, L=5mm, h=5mm



Res. freq. of pin hole w.r.t. the depth of neck
φ=1/4in., a=1mm, h=5mm

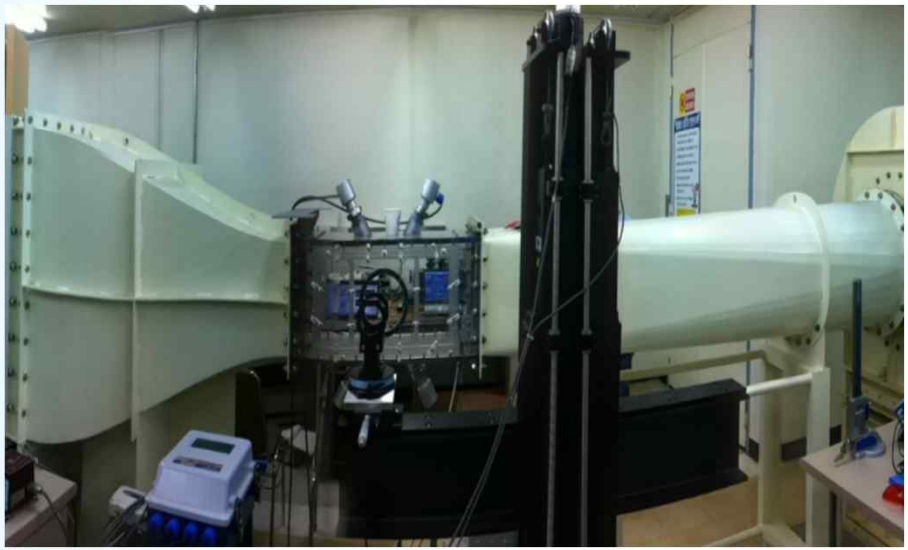


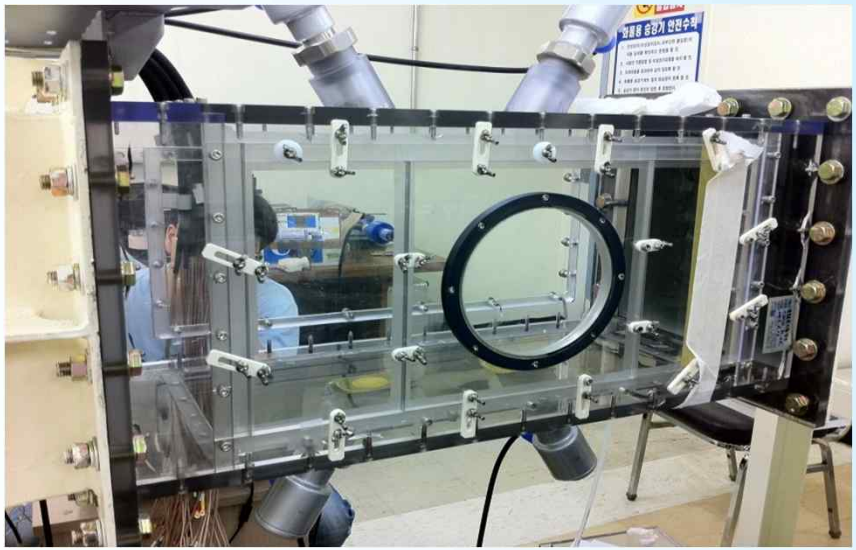
Res. freq. of pin hole w.r.t. the cavity depth in front of mic.
φ=1/4in., a=1mm, h=3mm

Flow Noise Measurement & Analysis

❖ WT experiments

Measurement section (size): 300mm(W) X 300mm(H) X 600mm(L)





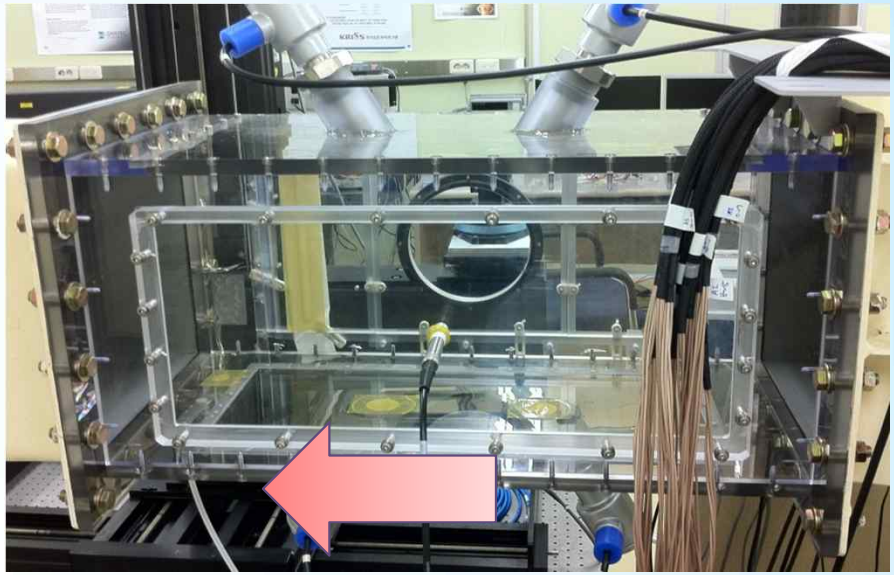
Used microphone (ECM/ HJ06)

Flow Noise Measurement & Analysis

❖ WT experiments

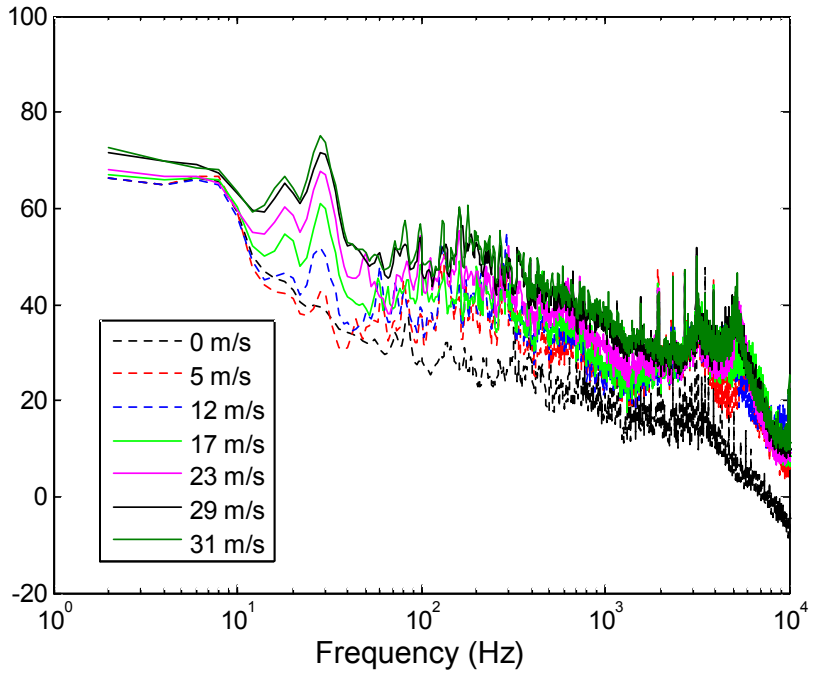
✓ Flow velocity

fan (rpm)	Flow vel. (m/s)
0	0
218	5
399	11.7
572	17.3
743	23.3
910	29.2
976	31.3



✓ Background noise measurement

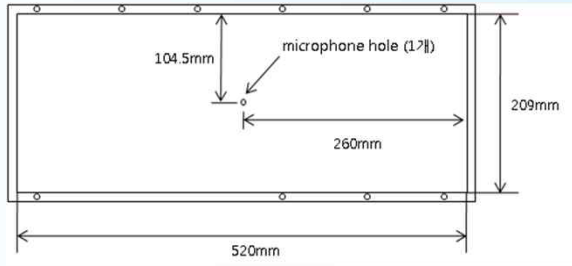
- ✓ suction fan noise
- ✓ fan controller noise
- ✓ vibration induced noise
- ✓ Outside of the test section

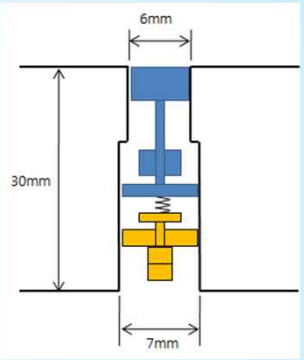


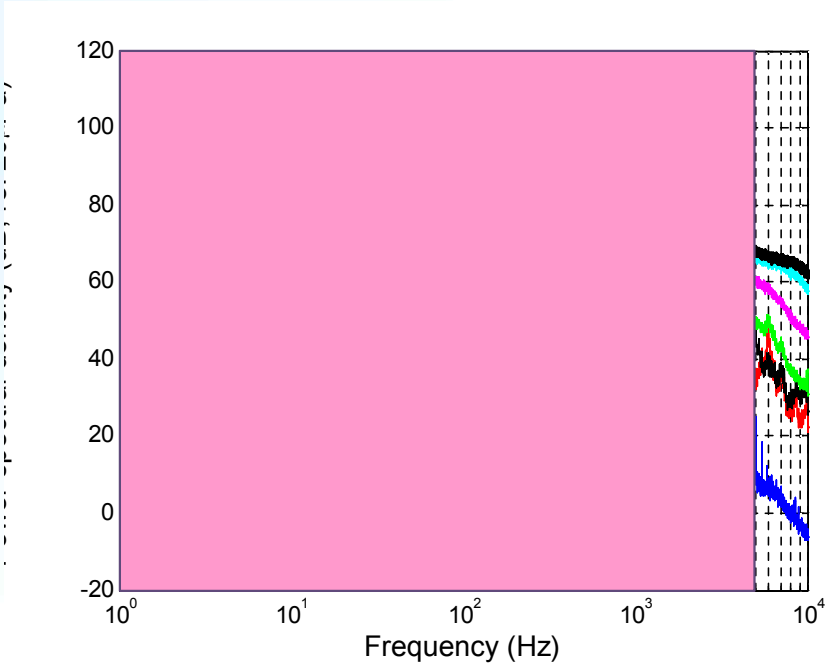
Flow Noise Measurement & Analysis

❖ Measured spectra

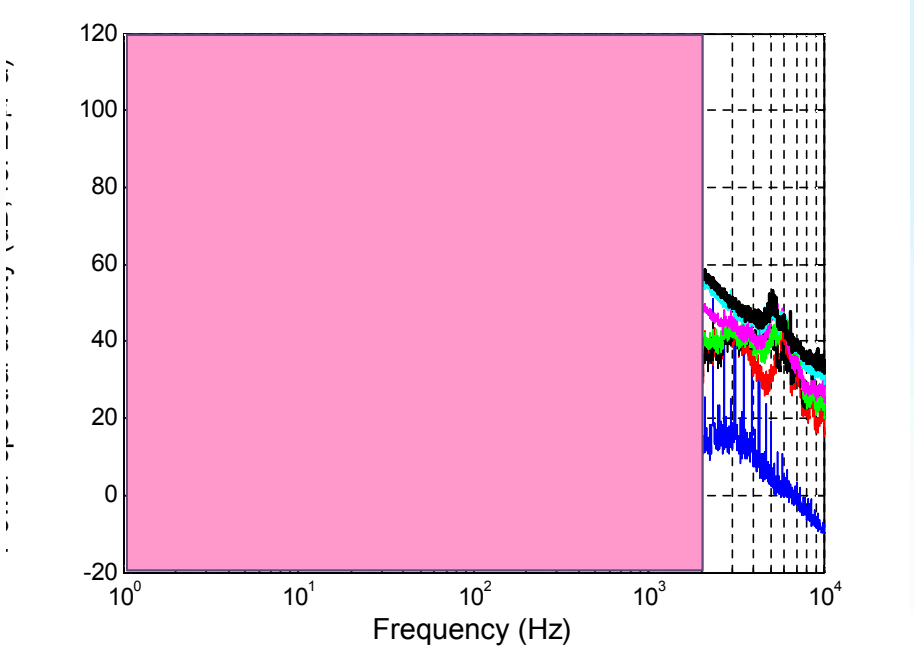
✓ Flush mounting







HJ07 microphones

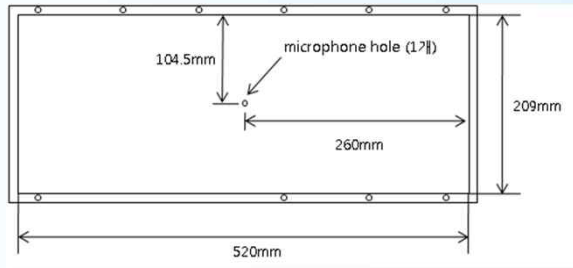


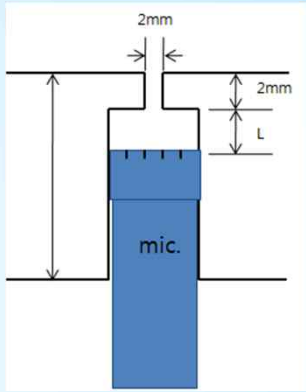
Type 46AD microphones

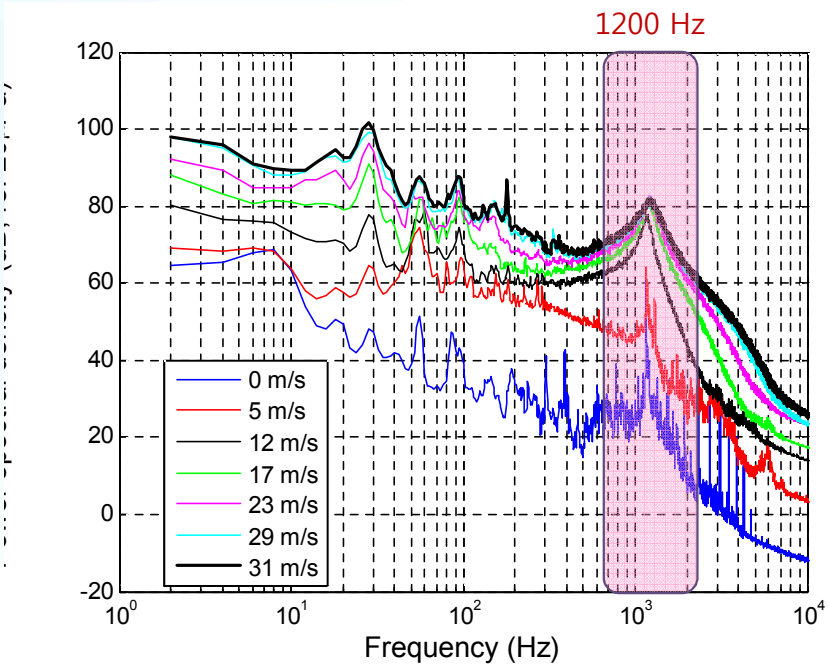
Flow Noise Measurement & Analysis

❖ Measured spectra

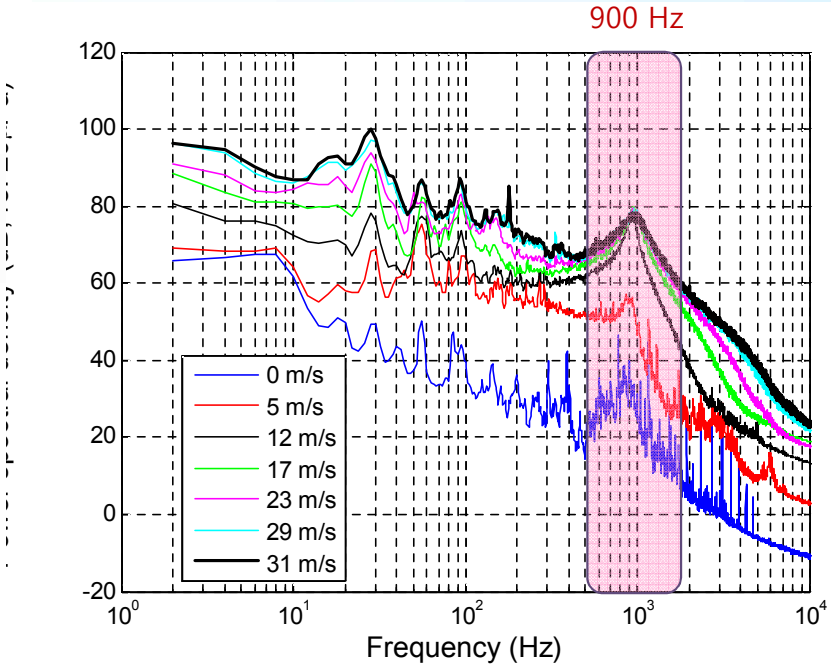
✓ Pinhole mounting







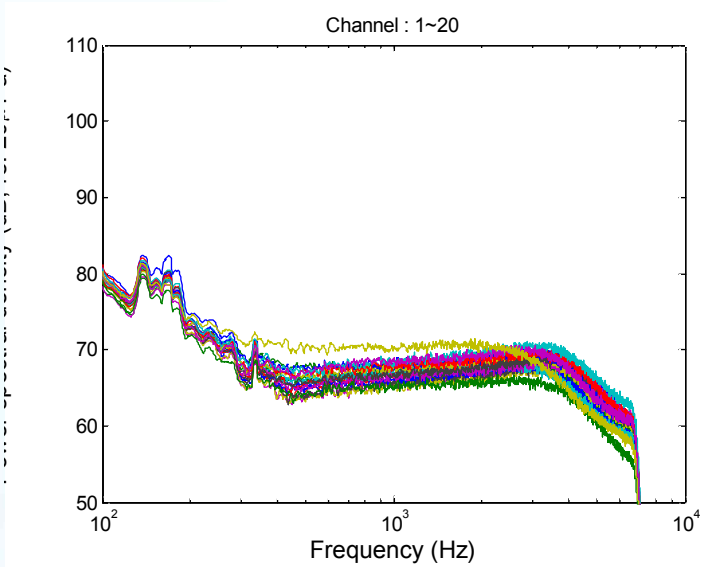
5 mm spacing between pinhole and mic.

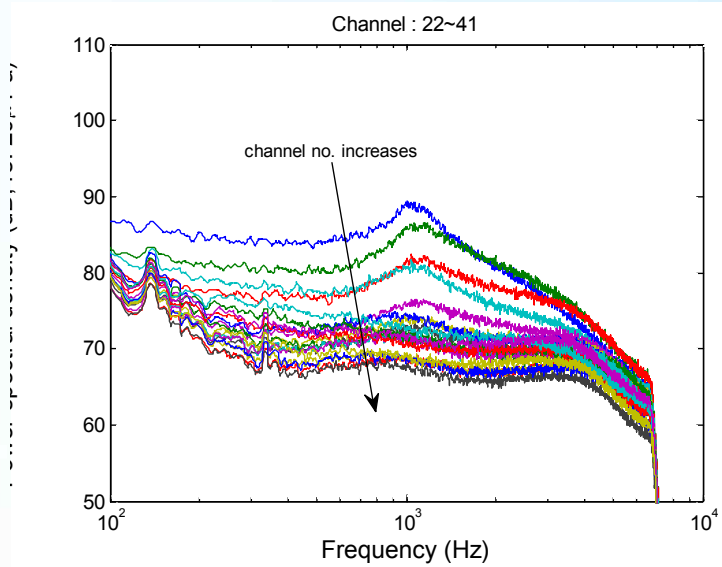


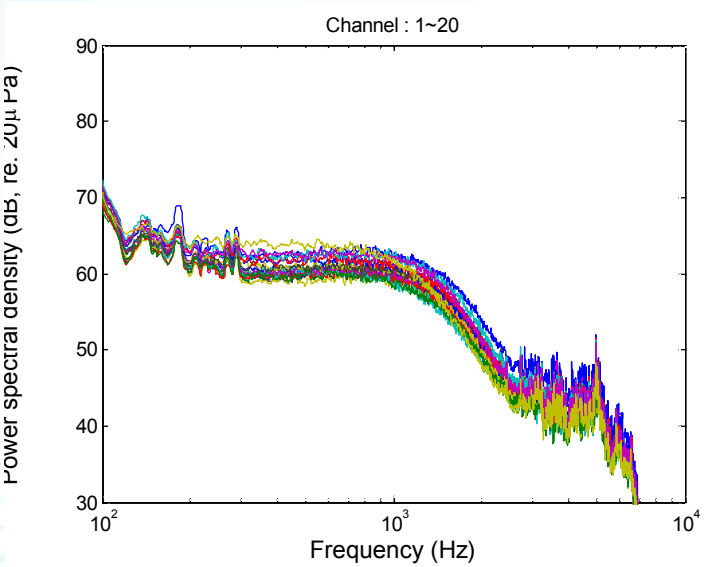
10 mm spacing between pinhole and mic.

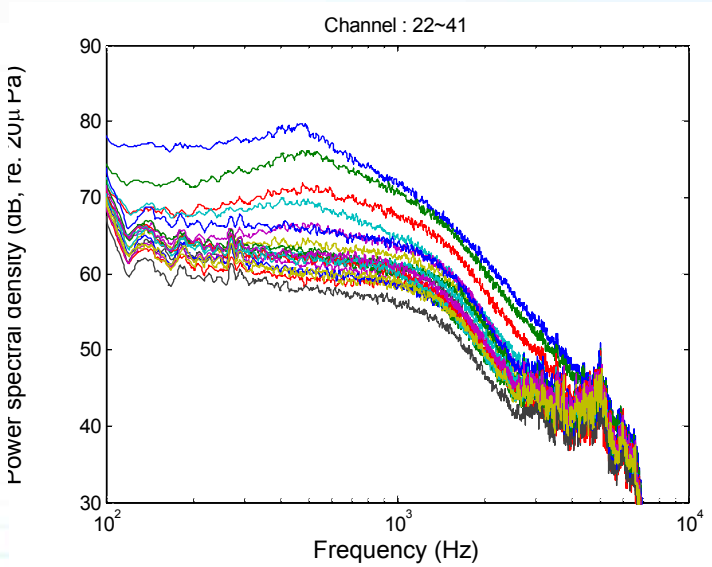
Flow Noise Measurement & Analysis

❖ Measured data analysis





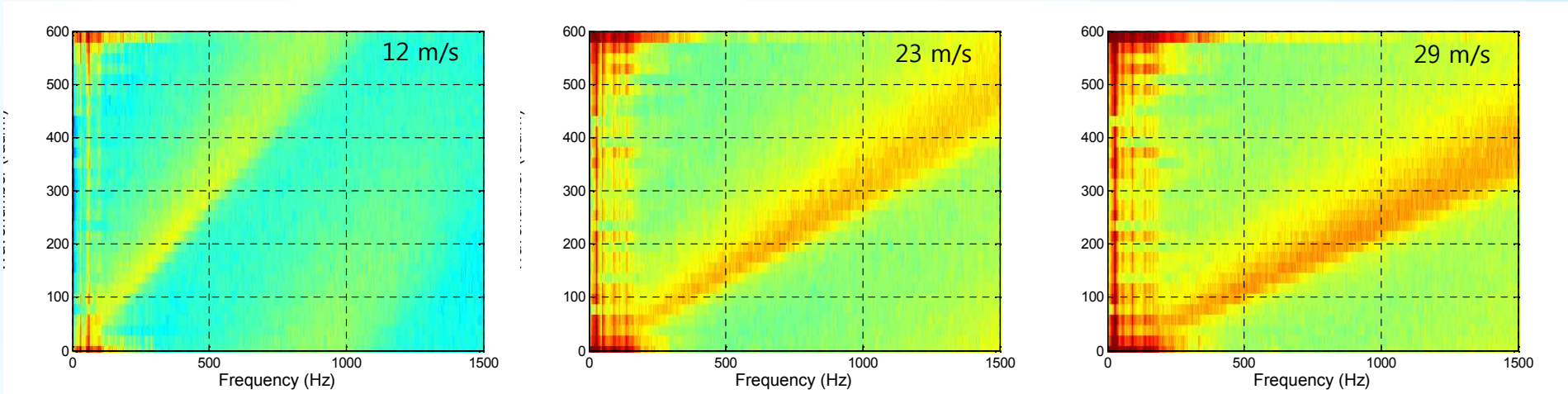




Flow Noise Measurement & Analysis

❖ Analysis (Convective velocity)

✓ Freq.-wavenumber analysis



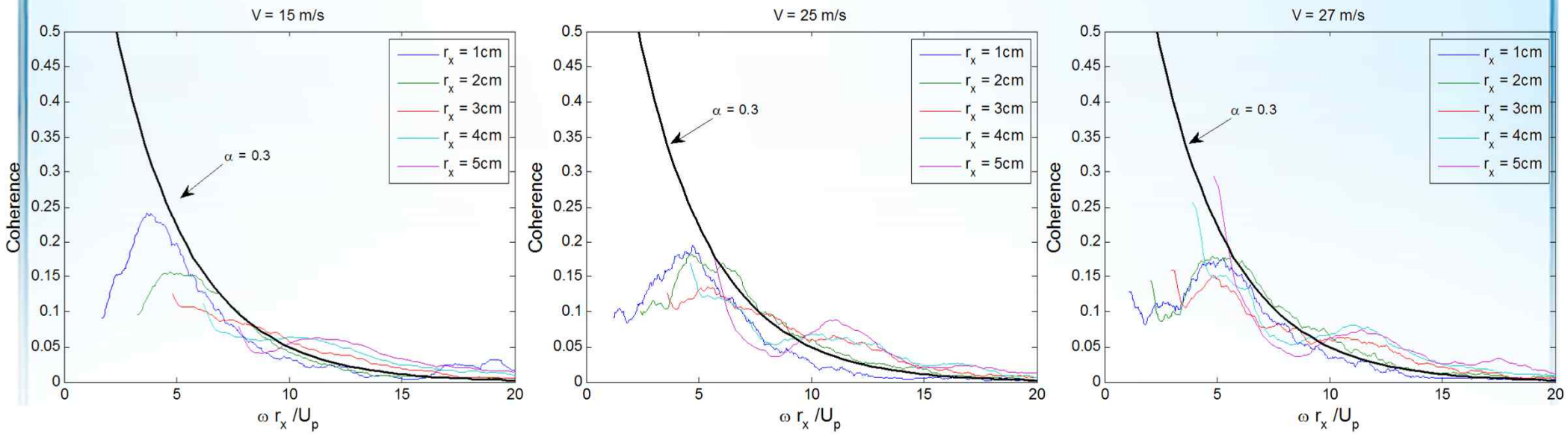
fan (rpm)	Flow vel. (m/s)	Conv. Vel. (m/s)
0	0	0
218	5	5.2
399	12	10.5
572	17	15.7
743	23	20.9
910	29	25.9
976	31	28.2

Flow Noise Measurement & Analysis

❖ Analysis (Corcos model parameters)

✓ Coherence

$$\gamma_{ab}^2(r,\omega) = \frac{|\phi_{ab}(r,\omega)|}{\phi_a(\omega) \cdot \phi_b(\omega)}$$



Flow Noise Measurement & Analysis

❖ Analysis: Flow induced vibration due to WPF

✓ Flow induced vibration of flat plate: Corcos model

- **Cross power spectral density function**

$$C_{pq}(\gamma_x, \gamma_y; \omega) = C_{pp}(\omega) A(\omega\gamma_x / U_c) B(\omega\gamma_y / U_c) e^{-j(\omega\gamma_x / U_c)}$$

$$A = \exp(-\alpha|\omega\gamma_x / U_C|) \qquad B = \exp(-\beta|\omega\gamma_y / U_C|)$$

0.3 0.7

- **Theoretical vibration response induced by TBL WPF**

$$-D_E \nabla^4 w(x, y, t) + p(x, y, t) = \rho_s \frac{\partial^2 w(x, y, t)}{\partial t^2}$$

$$H(x, x', y, y'; \omega) = \frac{1}{\rho_s} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\phi_{mn}(x, y) \phi_{mn}(x', y')}{\omega_{mn}^2 - \omega^2}$$

$$\phi_{mn}(x, y) = \frac{2}{\sqrt{\rho_s L_x L_y}} \sin\frac{m\pi x}{L_x} \sin\frac{n\pi y}{L_y} \qquad \omega_{mn} = \pi^2 \sqrt{\frac{D_E}{\rho_s}} \left\{ \left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2 \right\}$$

Flow Noise Measurement & Analysis

❖ Analysis: Flow induced vibration due to WPF

✓ Flow induced vibration of flat plate: Corcos model

- **Cross power spectral density function**

$$S_{uu}(x, y, \xi, \eta; \omega) = \int_0^{L_y}\int_0^{L_y}\int_0^{L_x}\int_0^{L_x} C_{pq}(\xi', \eta'; \omega)\, H(x, y, x', y'; -\omega)$$

$$H(x+\xi, y+\eta, x'+\xi', y'+\eta'; \omega)\, dx'\, d\xi'\, dy'\, d\eta'$$

$$= \sum_{j=1}^{m}\sum_{jj=1}^{m}\sum_{i=1}^{n}\sum_{ii=1}^{n} C_{pq}(\xi_{ii}', \eta_{jj}'; \omega)\, H(x, y, x_i', y_j'; -\omega)$$

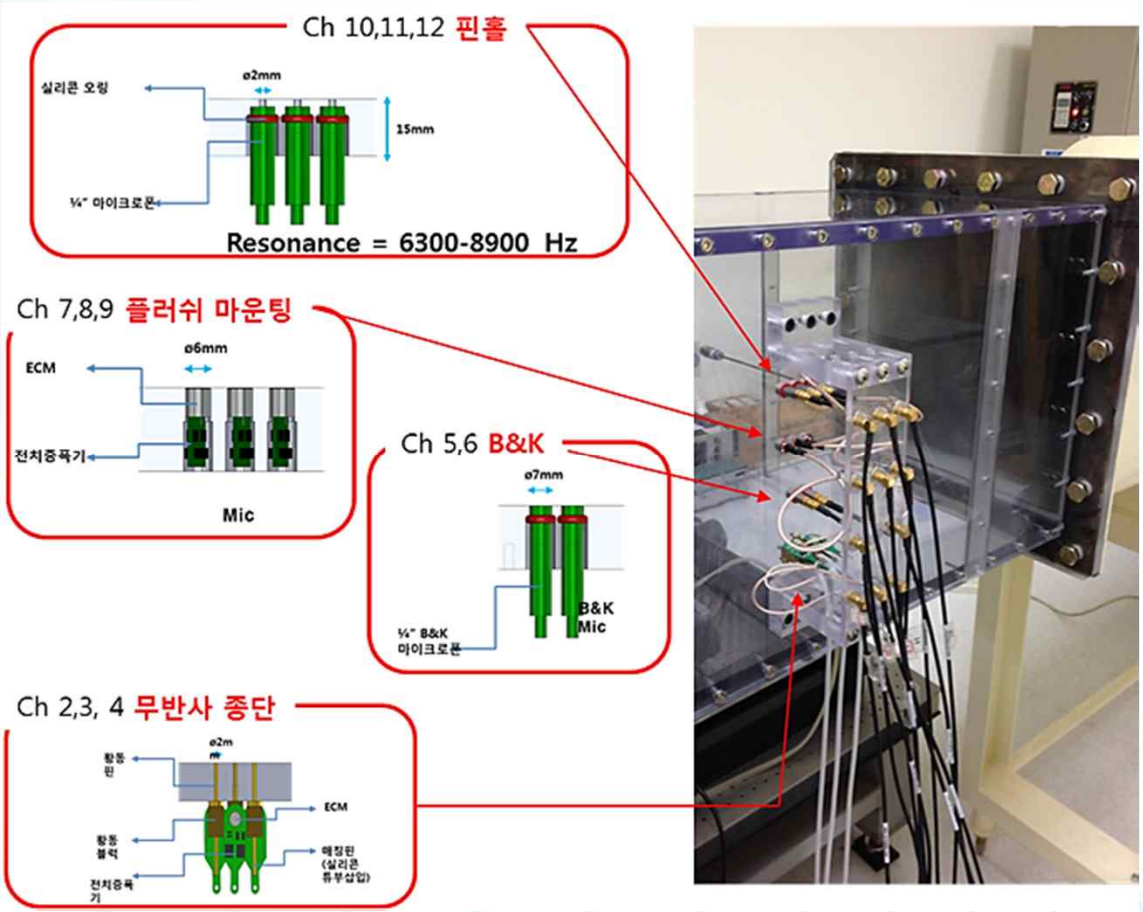
Cross power spectral density function

$$H(x+\xi, y+\eta, x_i'+\xi_{ii}', y_j'+\eta_{jj}'; \omega)\, \Delta x'\, \Delta\xi'\, \Delta y'\, \Delta\eta'$$

Flow Noise Measurement & Analysis

❖ Comparison of microphone mounting conditions

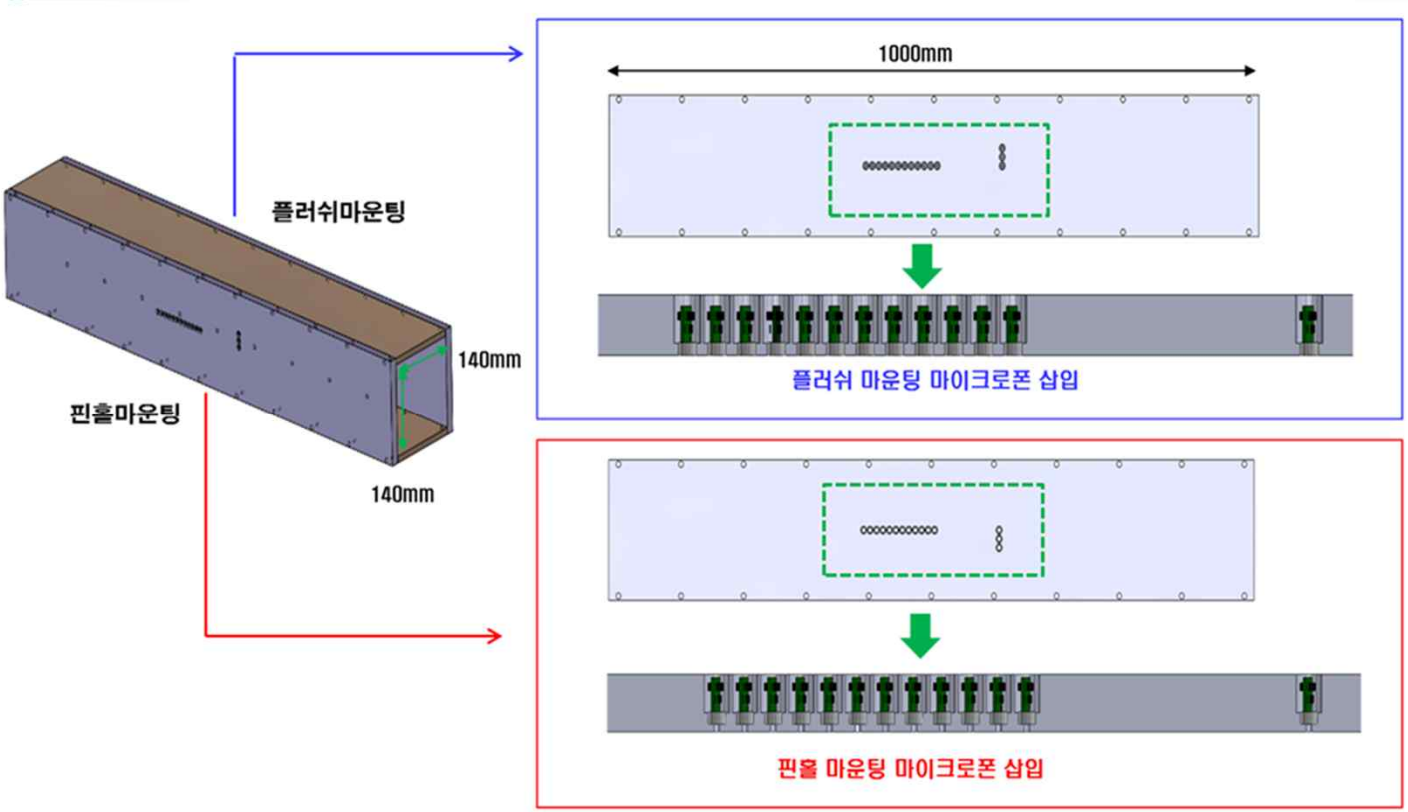
- ✓ **Spectral analysis relative to flow vel. (10, 20, 30 m/s)**
- ✓ **Measurement conditions**
  - Lines: 3200, Span: 25.6 kHz, df: 8 Hz, Averages: 300
  - Overlap: 66.67%, Recording time: 12.58s, High Pass Filter: 7 Hz



Flow Noise Measurement & Analysis

❖ Measurement setup (microphone arrays for flow noise)

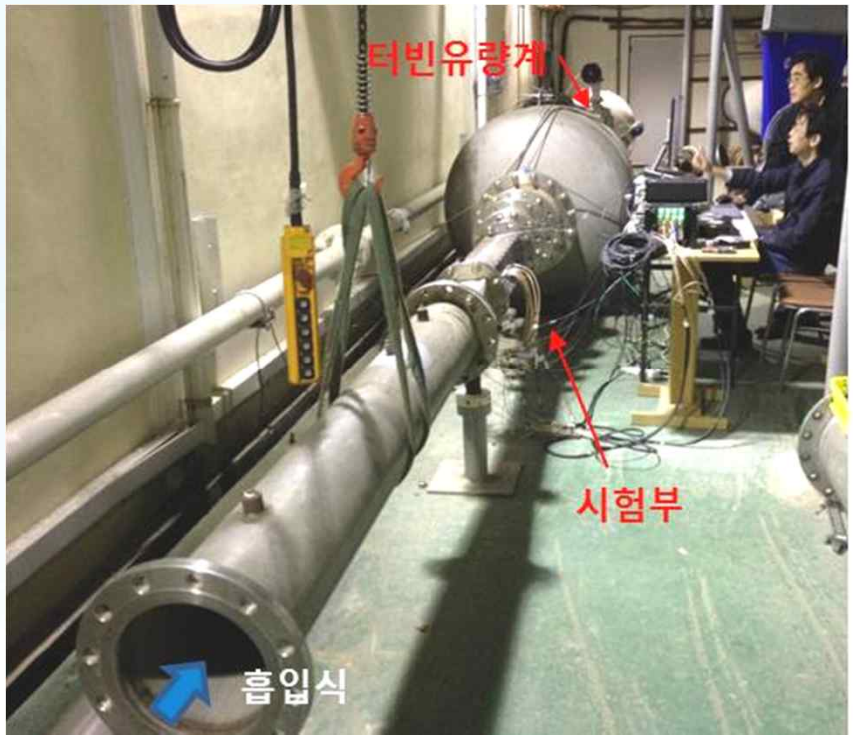
- ✓ Flush mounting & Pinhole mounting simultaneously
- ✓ Horizontal 6 pts. & vertical 3 pts. (10 mm spacing)



Flow Noise Measurement & Analysis

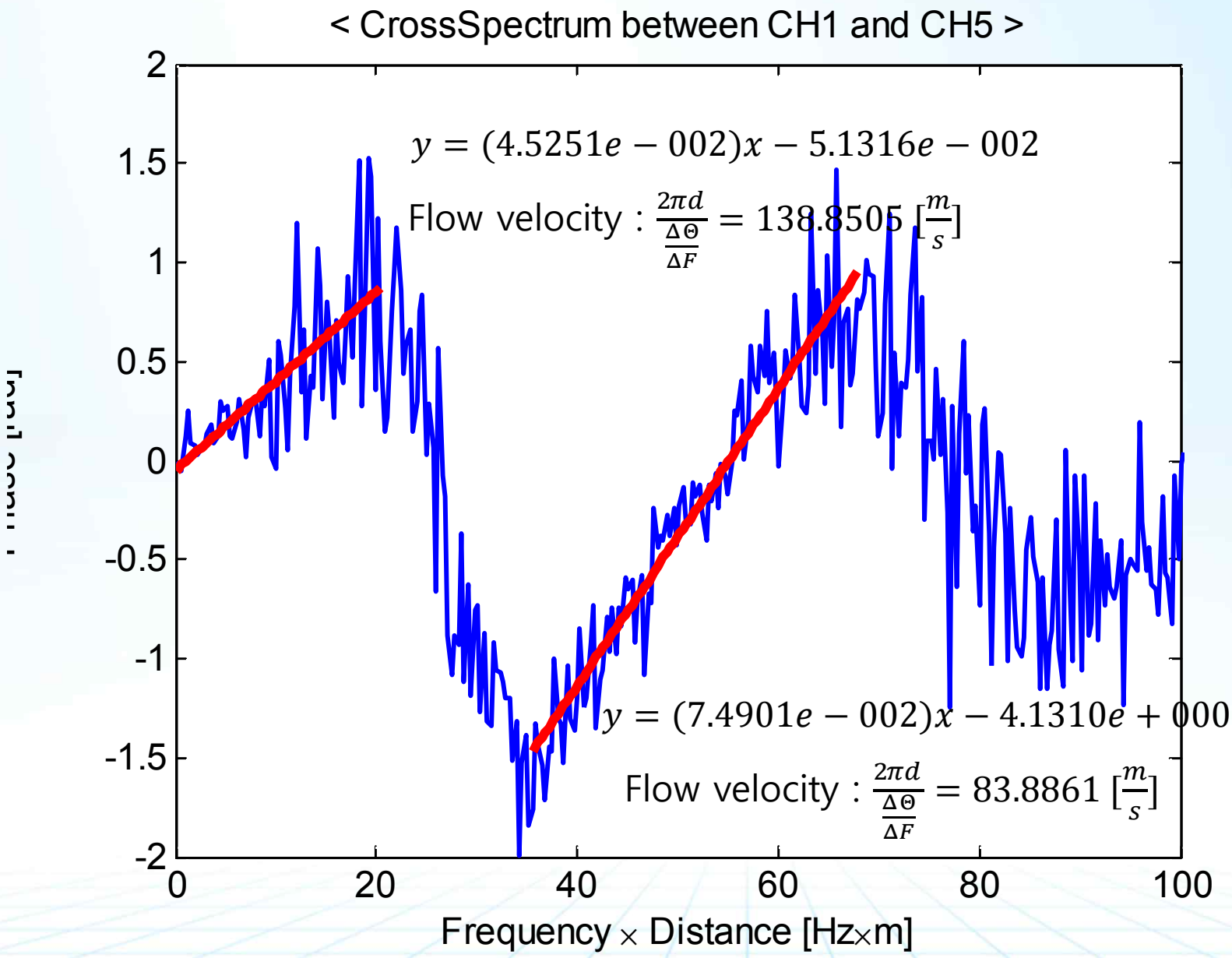
❖ **Measurement setup (microphone arrays for flow noise)**

- ✓ Reducing the noise of sonic nozzle (64 m/s)
- ✓ 1600 spectral lines, 25.6 kHz span, 500 average, ..

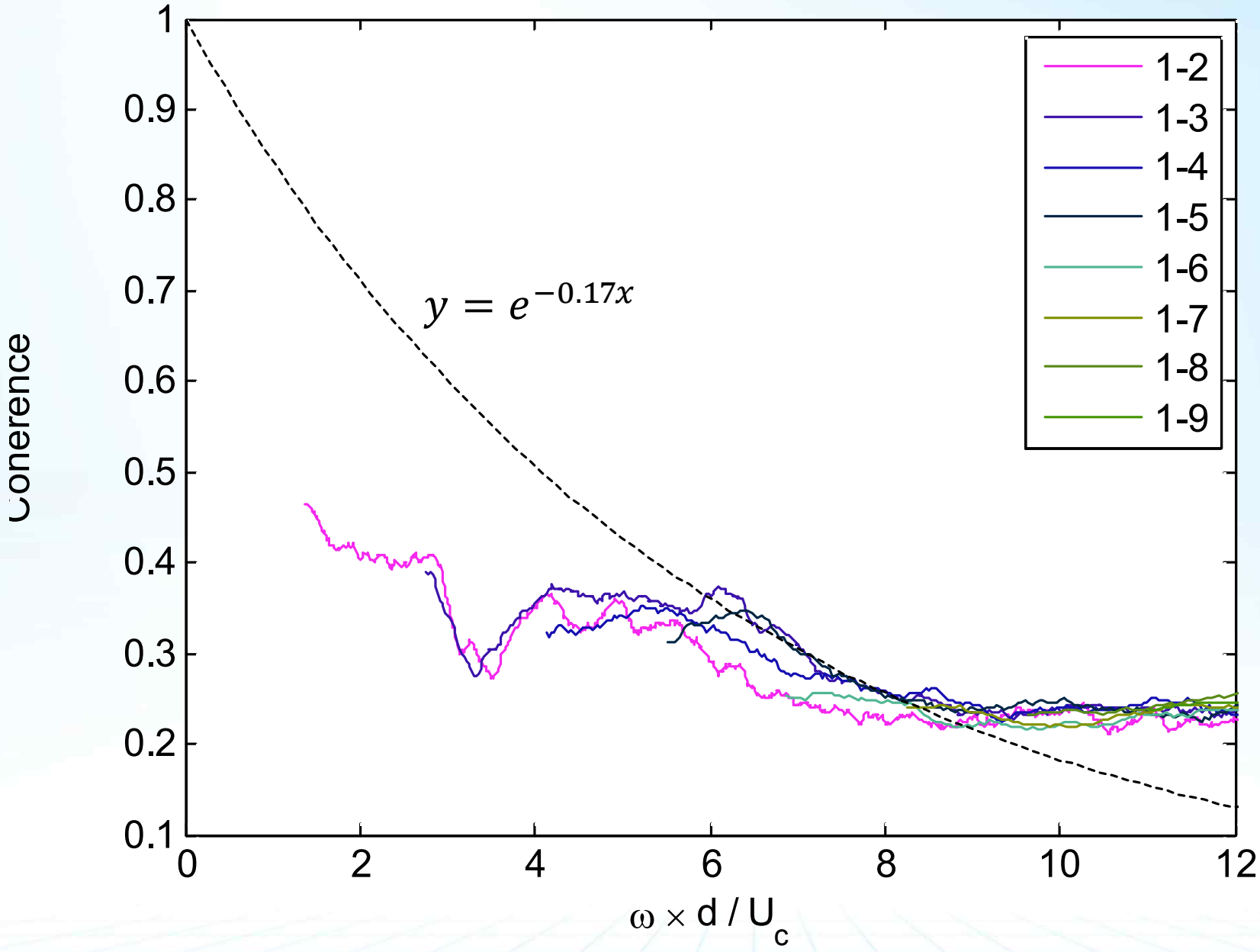


Flow Noise Measurement & Analysis

- **Convection Velocity from Phase of Cross Spectrum**

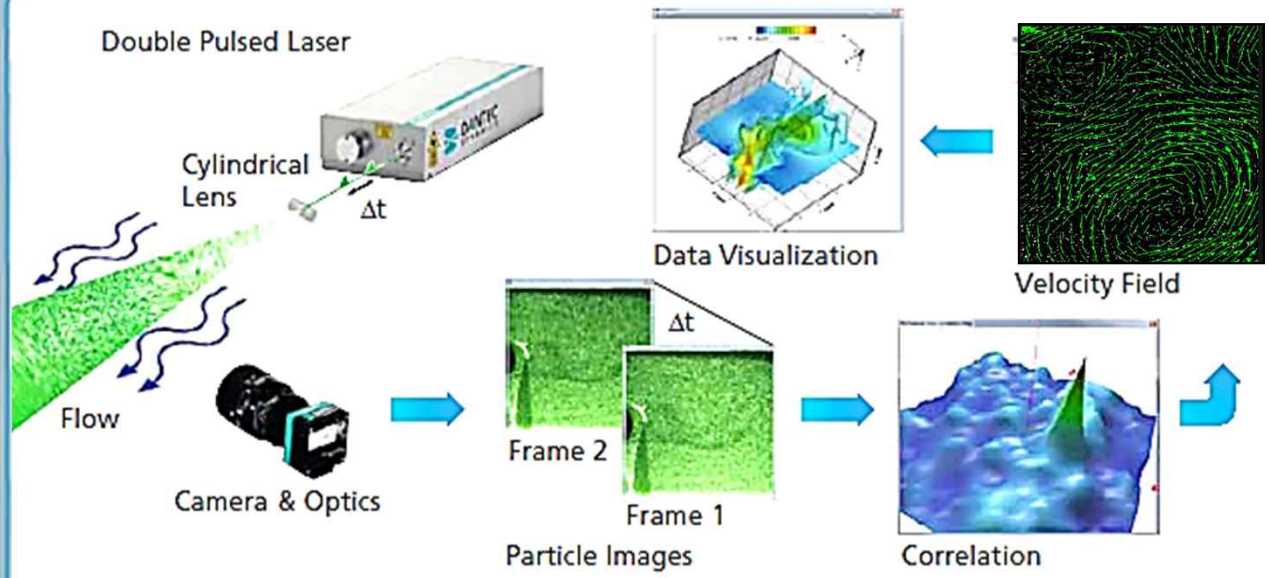


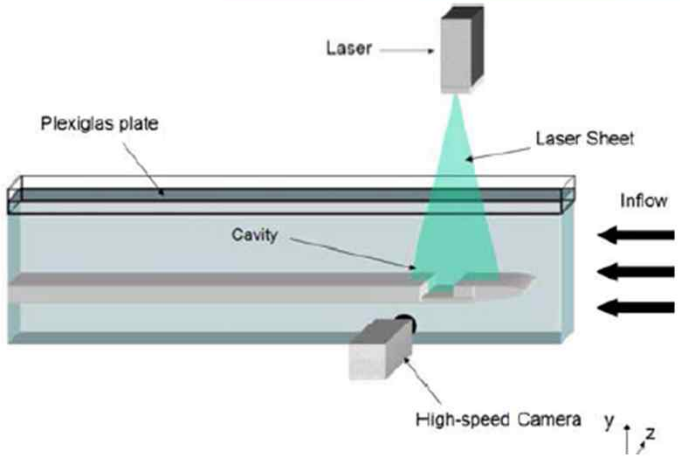
Flow Noise Measurement & Analysis



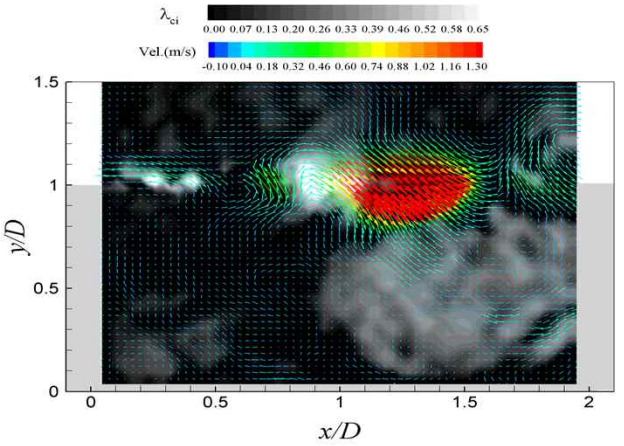
Stream-wise Decay Rate from Coherences

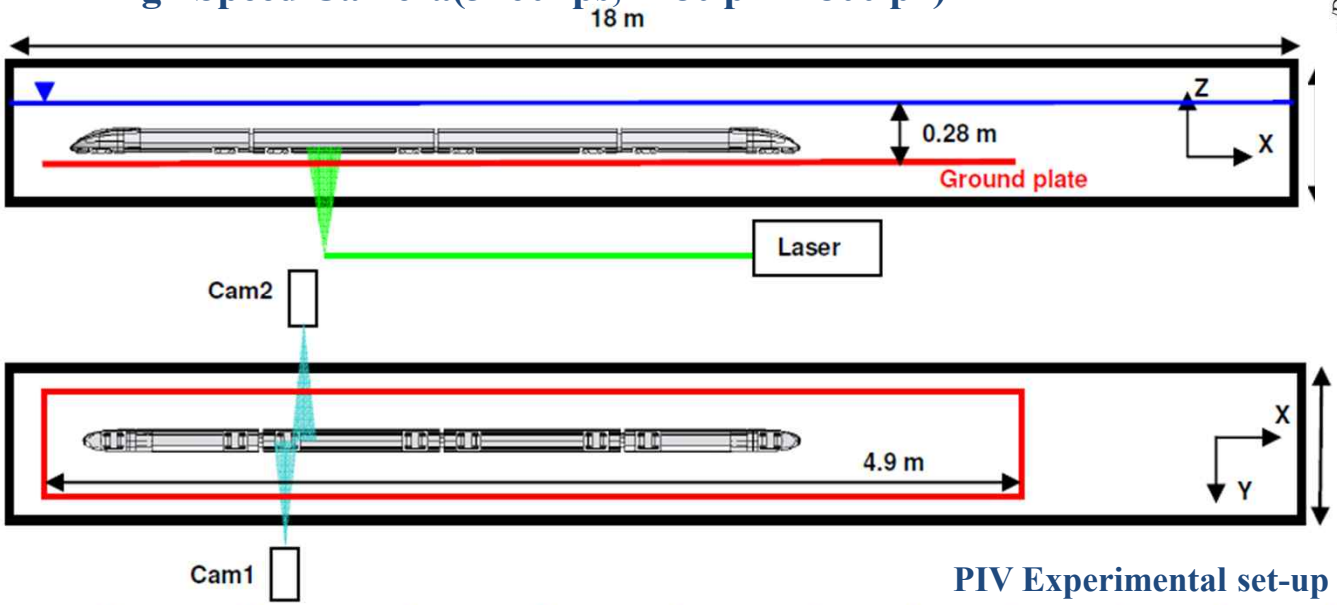
Future works

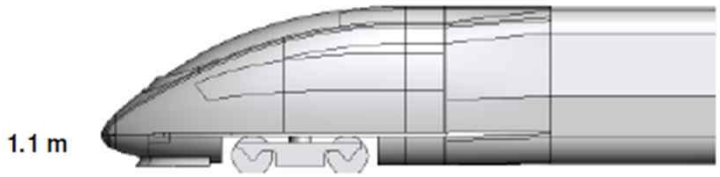




Time Resolved Lasers (20mJ @ 1kHz, max 20kHz)
High Speed Camera(3260 fps, 1280 px X 800 px)







PIV Experimental set-up

Thank you