

**Influence of sound source movement
on radiated sound characteristics
at low Mach number**

Yusuke Makino

Influence of sound source movement
on radiated sound characteristics
at low Mach number

A Dissertation

Presented to the Graduate School of Engineering
of Kyoto University

in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy (Engineering)

by

Yusuke Makino

October 2025

Abstract

Continuous exposure to noise has been found not only to cause discomfort to individuals but also to increase health risks such as cardiovascular diseases, cognitive impairment in children, sleep disturbances, tinnitus, and other adverse effects on the human body. To understand the actual state of noise pollution in urban areas, noise prediction models or frameworks based on a database of noise sources and acoustic propagation calculations have been developed. In the case of transportation noise, the movement of the vehicle causes frequency modulation (Doppler effect) and amplitude modulation (change of the directivity) of the radiated sound while the effects of changes in the radiated sound characteristics are often neglected.

This dissertation aims to clarify the extent to which noise metrics of current noise prediction models or frameworks are underestimated by neglecting the frequency and amplitude modulation induced by source movement, and under what conditions such underestimations are more significant. Then it also aims to clarify what factors other than source speed affect the degree of this underestimation, which need to be taken into account for improved noise prediction models considering source movement. Note that Mach numbers of source moment below 0.3 are defined as low Mach numbers.

Firstly, Doppler factor is defined as the ratio of frequency of radiated sound at a receiver to the pulsation frequency of the source. Radiated sound pressure of a moving point source is analytically derived and expressed as a power of the Doppler factor while the exponent of the pressure depends on their physical mechanisms.

Secondly, a scaled train model experiment was conducted to measure the directivities of simplified vibrational and aerodynamic sound sources. As the vibrational source, an ultrasonic transducer was attached to the train model. As the aerodynamic source, a cylinder was also attached to the model and then directivities of an aeolian tone sound generated using the cylinder were measured for a simplified dipole component of aerodynamic sound, which is generated from pressure fluctuation. The experimental results show

that the acoustic intensity of sound radiated from a vibrational source increase roughly in proportion to the fourth power of the Doppler factor, whereas that of the dipole component of aerodynamic sound increases roughly in proportion to the eighth power of the factor. Sound radiated from an aerodynamic source moving at low Mach numbers leads to a larger amplitude modulation due to source movement compared with sound radiated from a vibrational source, indicating the necessity of applying corrections for the sound source movement for each type of sound source in noise prediction models.

Thirdly, the directivities of an aeolian tone sound radiated from the cylinder fixed in a wind tunnel were measured with microphones outside the flow. Then amplitude modulation of the sound by convection was compared with the modulation of the same sound by source movement. The result revealed that an aerodynamic sound leads to a larger amplitude modulation by source movement compared with the modulation measured in a wind tunnel experiment, although the apparent wavelength of sound radiated from the same source in the atmosphere changes by the same proportion. It thus suggests that the radiated sound pressure level of an aerodynamic sound estimated in wind tunnel experiments may be underestimated compared to the level of the same aerodynamic source which is actually moving in the air.

Fourthly, transportation noise sources are simplified as a series of point sources at a constant velocity along a straight track. Then it is investigated how frequency and amplitude modulation due to source movement affect the noise metrics used in transportation noise prediction models. When frequency and amplitude modulation are considered, the computed metrics become larger than the levels without their consideration. The level difference between the cases increases with respect to the source velocity while it is independent of distance between the track and the observer. The level difference decreases monotonically with respect to the source frequency. Therefore, these findings suggest that neglecting source movement may lead to underestimation in transportation noise prediction at higher source velocities and lower source frequencies.

Finally, this dissertation can be concluded that ignoring frequency and amplitude modulation due to source movement, as the existing transportation noise prediction models, may underestimate the noise metrics and the underestimation becomes more significant for sources moving at higher velocity. Improving the models more accurately by considering source movement requires considering its physical mechanism, the method for measuring or estimating directivity, and its frequency characteristic as well as source velocity.

Acknowledgment

This dissertation summarizes the research which I conducted while enrolled in the doctoral program in the Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University. At first, I would like to appreciate my supervisor, Prof. Makoto Otani for the critical comments and suggestions at the meetings. I would also like to appreciate Prof. Kazunori Harada and Prof. Daisuke Ogura, the referees of my dissertation, for taking part in the thesis advisory committee and giving me insightful comments and advice at the defense.

From my undergraduate thesis to the middle of my doctoral program, Prof. Emeritus Yasushi Takano of Kyoto University, served as my supervisor. I would like to express my utmost respect and gratitude to him. Without my encounter with him in my laboratory, the research into transportation noise focusing on sound sources described in my dissertation would never have begun. As well as that, during the time I was working on my research, his constant encouragement, support, critical comments and suggestions, and patient guidance always helped me conduct the research and develop the foundation as a researcher. Moreover, I learned a lot about the vision, values, and philosophy that are not limited to research, which will be a guide for me.

The scaled train model experiment and the wind tunnel experiment in Chapter 3 and 4 in this dissertation were conducted as collaborative research among Railway Technical Research Institute (RTRI), Waseda University, and Kyoto University. I would like to acknowledge Dr. Mariko Akutsu and Dr. Toki Uda (RTRI) for their collaboration in these experiments. They helped me carry out my research in every respect, particularly in the experiments. I appreciate their support in and out of the laboratory, meetings, and the experiments. Especially, Dr. Akutsu entered the doctoral program in the same year as me. Although she and I are enrolled in different universities, we have encouraged each other and worked hard towards our doctoral degrees. I would like to thank her for that as well.

I completed this dissertation after leaving the doctoral program and joining Kobayasi Institute of Physical Research (KIPR). During the writing process, my supervisor at KIPR, Dr. Tetsuya Doi, the Director of Noise and Vibration Division, provided me with warm support, advice, and encouragement. Dr. Masaaki Hiroe, Dr. Tetsuya Doi, and Dr. Tomohiro Kobayashi are not only my colleagues or supervisors but also authors of prior studies referenced in this dissertation. I would like to appreciate them for offering valuable insights as pioneers in the study of radiated sound from moving sources. I would also like to thank for all the other colleagues of KIPR for heartfelt encouragement and support. I could not complete this dissertation in parallel with my work at KIPR without helps.

I would like to thank for Prof. Takao Tsuchiya of Doshisha University for his valuable advice and fruitful discussions about Doppler shift and amplitude modulation of moving sources.

Finally, I would like to acknowledge the members of our laboratory, Environmental Acoustics Laboratory. I would like to appreciate Mr. Hiraku Okumura, Dr. Takumasa Tsuruha, Mr. Ryo Matsuda, Mr. Yuto Izumi, and Dr. Tatsuhiko Tanaka, the colleagues of our laboratory during the doctoral program for fruitful discussion in and out of the laboratory. I also would like to appreciate all the present and former students and colleagues in the laboratory. I would like to acknowledge not only them but also Dr. Kazuki Ishikawa, Dr. Anyang Sun, Dr. Ryo Yamada, and Dr. Hajime Takayama, which are the colleagues of the doctoral program of the graduate school of Engineering, Kyoto University. I would appreciate them for critical question and fruitful comments in the meetings, helps for administrative procedures during the doctoral program, and encouragement. I am especially grateful to Ms. Mikiko Natori and Ms. Saeko Yano for the administrative assistance and warm encouragement.

This work was partly supported by Research Incentive Grant provided by Support for Pioneering Graduate Students presented by the Kyoto University Graduate Division, and a Research Fellowship for Young Scientists (22J15527 and 22KJ1901) from JSPS, Japan. I also acknowledge the financial support from Kajima Ikueikai.

Contents

Abstract	iii
Acknowledgment	v
Acronyms and symbols	xix
1 Introduction	1
1.1 Background	1
1.1.1 Transportation noise prediction	1
1.1.2 Beamforming	5
1.2 Purpose	8
1.3 Structure of the dissertation	9
2 Amplitude modulation of a single source	13
2.1 Introduction	13
2.2 Frequency of radiated sound from a moving source	13
2.3 Amplitude modulation of moving sources with various physical mechanisms	15
2.4 Modulated wavelength and amplitude modulation due to convection	19
2.5 Summary	21
3 Measured amplitude modulation of moving sources	23
3.1 Introduction	23
3.2 A train model experiment	26
3.2.1 A scaled train model	26
3.2.2 Low-noise moving model test facility	27
3.2.3 Measurement of sound source position and velocity	28
3.2.4 Measured directivities of moving sources	31

3.2.5	Results	34
3.3	Discussion	34
3.3.1	Source term	34
3.3.2	Doppler factor and amplitude modulation due to source movement	38
3.4	Summary	40
4	Source movement and convection of aeolian tone sound	41
4.1	Introduction	41
4.2	Wind tunnel experiment	43
4.2.1	Wind tunnel	43
4.2.2	Flow velocities at the source position	44
4.2.3	SPL of an aeolian tone	45
4.2.4	Correcting the refraction of a shear layer	47
4.2.5	Results	49
4.3	Amplitude modulation due to convection	50
4.4	Discussion	55
4.5	Summary	56
5	Influence of source movement on noise metrics	57
5.1	Introduction	57
5.2	Radiated sound from a moving source	59
5.2.1	Radiated sound pressure	62
5.2.2	A-weighted SPL	64
5.2.3	Time weighting S (slow)	65
5.2.4	Equivalent continuous sound level	65
5.2.5	Doppler effect	66
5.2.6	Amplitude modulation	66
5.3	Change of noise metrics	72
5.3.1	Source discretization	72
5.3.2	Change of noise metrics at various velocity and distance from the source track	75
5.3.3	Noise metrics of a sound source group and a finite source line . . .	80
5.4	Influence of source frequency on relative SPLs	83
5.5	Exponent of relative SPLs	85

5.6	Summary	87
6	Conclusion	89
6.1	Summary	89
6.2	Future prospects	92
6.2.1	Compatibility with geographical features and surrounding environments	92
6.2.2	Improved operating speeds of railway vehicles and compliance with environmental standards	93
6.2.3	Development of research on health risks caused by noise	93
6.3	Future issues	94
	Bibliography	97
A	Corrected sound pressure for the refraction of a shear layer	115
B	Validity of approximations in deriving sound pressure	121
C	Changes of noise metrics	123

List of Tables

1.1	Disability-Adjusted Life Year (DALY) by environmental noise in Western Europe [1].	2
1.2	Recommended noise levels by Environmental noise guidelines for the European region [2].	2
4.1	Estimated flow velocities V_{flow} [m/s], Mach numbers of air flow M_{flow} , and Reynolds numbers Re at the sound source position.	46
5.1	Normalized railway noise spectrum [113].	70

List of Figures

1.1	The NOISE Observation & Information Service for Europe by European Environment Agency [4].	3
1.2	A noise map for railway noise in Chicago, the United States [5].	4
1.3	A noise map for road traffic noise in Osaka City, Japan [7].	4
1.4	The schematic of Delay and Sum beamforming (DAS) [14].	6
1.5	Outline of this dissertation.	10
2.1	A moving source $\mathbf{r}_{\text{source}}(t)$ at velocity vector $\mathbf{V}(t)$ and a microphone $\mathbf{r}_{\text{mic}}$	14
2.2	A monopole point source (pulsating sphere).	15
2.3	Cross section of a cylinder in air flow generating an aeolian tone as a simplified dipole component of an aerodynamic sound.	17
2.4	Jet from a nozzle radiating a quadrupole component of an aerodynamic sound.	18
2.5	A sound source $\mathbf{r}_{\text{source}}(t)$ and a microphone $\mathbf{r}_{\text{mic}}$ in a flow at velocity $\mathbf{V}_{\text{flow}}$ from the viewpoint of an observer moving with the air flow.	20
3.1	A scaled train model with two sound sources.	26
3.2	An aerodynamic sound source used in a scaled train model experiment.	27
3.3	Setup of a scaled train model in a semi-anechoic chamber at a low-noise moving model test facility.	28
3.4	Position of a vibrational sound source, an aerodynamic sound source, and 1/4-inch microphone.	29

3.5	Spectrograms of sound recorded by a 1/4-inch microphone, and estimated frequencies of sound radiated from two sources at velocities of (a)197, (b)242, and (c)277 km/h when a vibrational sound source passed directly under the microphone. (White dashed lines: a vibrational sound source; black dashed lines: the cylinder of an aerodynamic sound source). Straight white dotted lines represent the times $t_{f,\text{source}}$ [s] when a peak frequency of radiated sound from the vibrational sound source is closest to f_{source} at the microphone and straight black dotted lines represent the time $t_{\text{peak,AE}}$ [s] when the SPL of the sound radiated from an aerodynamic sound source reaches the peak at the microphone.	31
3.6	Spectra of sound recorded by a 1/4-inch microphone at the time when the SPL of the sound radiated from an aerodynamic sound source reaches the peak. The velocities of the scaled train model are (a)197, (b)242, and (c)277 km/h when a vibrational sound source passed directly under the microphone. (Straight dashed lines: the estimated frequencies of the aeolian tone from the cylinder of an aerodynamic sound source at the time; straight dotted lines: the frequencies ± 0.75 kHz.)	33
3.7	Measured directivities $L_{\text{dir}}(\theta)$ [dB] of a vibrational sound source on a scaled train model moving at different velocities: (a)108 km/h, (b)109 km/h, (c)109 km/h, (d)155 km/h, (e)197 km/h, (f)240 km/h, (g)241 km/h, (h)241 km/h, (i)241 km/h, (j)242 km/h, (k)277 km/h, and (l)289 km/h.	35
3.8	Measured directivities $L_{\text{dir}}(\theta)$ [dB] of an aerodynamic sound source measured in a scaled train model experiment: (a)197 km/h, (b)242 km/h, and (c)277 km/h.	35
3.9	Geometry of an aerodynamic sound source $\mathbf{r}_{\text{source}}$, an image aerodynamic sound source $\mathbf{r}'_{\text{source}}$, and a microphone $\mathbf{r}_{\text{mic}}$	37
3.10	Amplitude modulations due to source movement $\Delta L_{\text{Doppler}}$ [dB] of a vibrational sound source, as measured in a scaled train model experiment. (Straight broken line: linear regression of plotted data.)	38
3.11	Amplitude modulations due to source movement $\Delta L_{\text{Doppler}}$ [dB] of an aerodynamic sound source, as measured in a scaled train model experiment. (Straight broken line: linear regression of plotted data.)	39
4.1	A sound source in a wind tunnel and 14 microphones aligned horizontally.	43

4.2	Positions of a cylinder of an aerodynamic sound source and 14 microphones, and the region of the flow and the shear layer in the wind tunnel.	44
4.3	Measured sound spectra of the aeolian tone from the aerodynamic source ((b) $x_{\text{AE}} = 0.7$ m) at the microphone located at $x_{\text{mic}} = 0.7$ m, where the flow velocity setting was (i)54.2 m/s (195 km/h), (ii)66.7 m/s (240 km/h), and (iii)77.8 m/s (280 km/h). (Solid lines and dotted lines represent the sound spectrum measured at the microphone with and without the sound source.)	46
4.4	Correction of refraction by a shear layer.	48
4.5	Normalized flow velocities (the ratios of the measured flow velocity to the flow velocity setting) of (iii)77.8 m/s (280 km/h). The $\times$ marks represent the positions which the flow velocity is so slow that it is supposed to be outside the flow. The area between the two dashed lines represents the estimated shear layer.	49
4.6	Measured directivities of a cylinder of an aerodynamic sound source $L_{\text{dir}}(\theta)$ [dB] at three different positions with three different flow velocity settings. (The influence of the shear layer was corrected and the measured data plotted with $\times$ marks were excluded from an analysis of amplitude modulation by convection.)	50
4.7	Retarded position of a cylinder of an aerodynamic sound source $\mathbf{r}_{\text{source,r}}$ and an image sound source of that $\mathbf{r}'_{\text{source,r}}$, and the corrected position of a microphone $\mathbf{r}_{\text{mic,c}}$	52
4.8	Ratios of the apparent wavelength $\lambda/\lambda_{\text{source}}$ of the sound radiated from a cylinder of an aerodynamic sound source and increases in SPL of the source by convection ΔL_{conv} [dB] measured in a wind tunnel experiment ((b) $x_{\text{AE}} = 0.7$ m) and by source movement $\Delta L_{\text{Doppler}}$ [dB] measured in a scaled train model experiment in Chapter 3.	53
4.9	Ratios of the apparent wavelength $\lambda/\lambda_{\text{source}}$ of the sound radiated from a cylinder of an aerodynamic sound source and increases in SPL of the source by convection ΔL_{conv} [dB] measured at all the three sound source position in a wind tunnel experiment and by source movement $\Delta L_{\text{Doppler}}$ [dB] measured in a scaled train model experiment in Chapter 3.	54
5.1	Calculation model.	61

5.2	Doppler effect due to a single source movement ($M = 0.1, 0.3$). When azimuth angle variation in time is considered, the time when calculated frequency of the radiated sound drops delay.	67
5.3	Computed A-weighted SPL L'_A [dB] and L_A [dB], and the level difference ΔL_A [dB] (source velocity: 300 km/h ($M = 0.245$), $r = 7.5$ m, $L_{wA} = 120$ dB, $N = 16$, source interval: 25 m). When frequency and amplitude modulation is considered, the maximum A-weighted SPL is observed just before the time when each source is at the closest position from the receiver shown by vertical dotted lines.	69
5.4	Normalized railway noise spectrum [113].	71
5.5	The model of finite line source and its calculation model.	73
5.6	Noise metrics for different source division N (source velocity: 100 km/h ($M = 0.082$), $r = 7.5$ m). Calculated levels decrease as the number of source division increases. The levels converge fast in order of $L_{Aeq, Tp}$, L_{ASmax} and L_{Amax} . All the levels converge at about $N = 10000$ within 0.1 dB.	73
5.7	Influence of finite line source velocity on noise metrics ($N = 10000$). Calculated levels L_{Amax} , L_{ASmax} and $L_{Aeq, Tp}$, when frequency and amplitude modulation are considered, are larger than the levels without their consideration.	76
5.8	Relative A-weighted SPLs ΔL_{Amax} [dB], ΔL_{ASmax} [dB] and $\Delta L_{Aeq, Tp}$ [dB] from Fig. 5.7. The differences of the calculated levels increase monotonically with respect to sound source speed with and without considering frequency and amplitude modulation, and they reach ca. 1.2 dB at a speed of 300 km/h.	77
5.9	Influence of finite line source velocity on noise metrics ($N = 10000$). Calculated levels L_{Amax} , L_{ASmax} and $L_{Aeq, Tp}$, when frequency and amplitude modulation are considered, are larger than the levels without their consideration.	78
5.10	Relative A-weighted SPLs ΔL_{Amax} [dB], ΔL_{ASmax} [dB] and $\Delta L_{Aeq, Tp}$ [dB] from Fig. 5.9. The differences of the calculated levels are independent of distance from the source track between the cases with and without considering frequency and amplitude modulation.	79

5.11	Influence of the source division N on noise metrics ($r = 7.5$ m). Calculated levels $L_{A\max}$ and $L'_{A\max}$ for $N = 16$ is larger than the results for $N = 10000$ (finite line source) by ca. 1.5 and 3.0 dB, respectively.	81
5.12	Influence of the source division N on noise metrics where source velocity is 300 km/h ($M = 0.245$). Calculated levels $L'_{A\max}$ for $N = 16$ are larger than the results for $N = 10000$ (finite line source) by ca. 1.0 dB.	82
5.13	Relative SPLs and relative A-weighted SPLs for different source frequencies at $r = 25$ m increase with velocity increase. Increase of A-weighted SPL is high at lower frequencies due to its frequency weighting.	84
5.14	Exponent $N_{\exp}$ of the relative SPLs and the relative A-weighted SPLs.	86
A.1	Calculated level difference of the corrected SPLs $ p_{c0p}(h \neq 0)/p_{c0p}(h = 0) $ [dB] between $h \neq 0$ and $h = 0$	118
A.2	Level difference of the corrected SPLs $ p_{c\infty p}/p_{c0p} $ [dB] between the cases where a shear layer is sufficiently thick and thin compared with the wavelength of the radiated sound ($h = 0.35$ m).	119
B.1	Approximation error of amplitude E_{amp} and approximation error of phase E_{ph} (source frequency: 20 Hz, $r = 7.5$ m). From the figure, it can be approximated as $p_n/\tilde{p}_n \approx 1$	122
C.1	Noise metrics for different source frequencies at $r = 7.5$ m.	124
C.2	Noise metrics for different source frequencies at $r = 25$ m.	125
C.3	Noise metrics for different source frequencies at $r = 50$ m.	126
C.4	Noise metrics for different source frequencies at $r = 100$ m.	127
C.5	Noise metrics for different source frequencies at $r = 200$ m.	128
C.6	Noise metrics for different source frequencies at $r = 400$ m.	129

Acronyms and symbols

Acronyms

Acronym	Meaning
DALY	Disability-Adjusted Life Years
END	Environmental Noise Directive
CNOSSOS-EU	Common NOise aSSessment methOdS in Europe
DAS	Delay and Sum beamforming
PPSI	Parallel Phase-Shifting Interferometry
RTRI	Railway Technical Research Institute
STFT	Short Time Fourier Transform
SPL	Sound Pressure Level
RMS	Root Mean Square
PWL	Power Level

Symbols

Chapter 2

Symbol	Meaning
$\mathbf{V}$	Vector of sound source velocity
V [m/s]	Sound source velocity
$\mathbf{V}_{\text{flow}}$	Vector of air flow
V_{flow} [m/s]	Air flow velocity
t [s]	Time
$\mathbf{r}_{\text{source}}$	Position vector of the center of a sound source
$\mathbf{r}_{\text{source,VIB}}$	Position vector of the center of a vibrational sound source
$\mathbf{r}_{\text{source,AE}}$	Position vector of the center of a cylinder of an arodynamic sound source
$\Delta\mathbf{r}_{\text{source}}$	Vector from $\mathbf{r}_{\text{source,VIB}}$ to $\mathbf{r}_{\text{source,AE}}$
$\mathbf{r}_{\text{mic}}$	Position vector of a stationary microphone
$\mathbf{R}$	Vector of propagating path from the source to the microphone
R [m]	Length of propagating path $\mathbf{R}$
θ [rad]	Angle between $\mathbf{V}$ and $\mathbf{R}$ of radiated sound
f [Hz]	Frequency of sound radiated from the source
f_{source} [Hz]	Pulsation frequency of the sound source
λ [m]	Apparent wavelength of the radiated sound
λ_{source} [m]	λ at the frequency f_{source}
c [m/s]	Speed of sound
M	Mach number of source movement
M_{flow}	Mach number of air flow
D_f	Doppler factor
ϕ [m ² /s]	Velocity potential
p [Pa]	Sound pressure

ρ [kg/m ³]	Air density
$\bar{q}$ [/s]	Rate of increase of fluid volume per unit volume of the fluid
$\bar{\mathbf{F}}$	Localized body force applied to the fluid per unit volume of the fluid
$\mathcal{F}$ [Pa/m ²]	Generalized pressure source in inhomogeneous wave equation
q [m ³ /s]	Volume velocity of a point sound source
$\mathbf{r}$	Position vector of a stationary observer
$\mathbf{F}$	External force acting on the point source
i (Subscript)	Component in the direction of each axis in the three-dimensional Cartesian coordinates
j (Subscript)	Component in the direction of each axis in the three-dimensional Cartesian coordinates
θ_i [rad]	Angle between the propagation direction of the radiated sound and each axis
θ_j [rad]	Angle between the propagation direction of the radiated sound and each axis
F_j [N]	External force acting on a point sound source
t_{ij} [N · m]	Element of turbulence stress tensor
S [kg/s ²]	Source strength of a pressure point source
τ [s]	Emission time

Chapter 3 and 4

Symbol	Meaning
Δx_{VIB} [m]	Distance in rail direction between the tip of the nose of the train model and the center of the vibrational source
Δx_{AE} [m]	Distance in rail direction between the tip and the center of the aerodynamic source
D [m]	Diameter of a cylinder of an aerodynamic sound source
St	Strouhal number
St_0	Intercept of Strouhal number
$St_{\text{coef.}}$	Coefficient of the Strouhal number
Re	Reynolds number
ν [m ² /s]	Kinematic viscosity
z_{mic} [m]	Distance in height direction between the surface of ground plates and microphones
z_{VIB} [m]	Distance in height direction between the surface of ground plates and the vibrational sound source
z_{AE} [m]	Distance in height direction between the surface of ground plates and the center of the aerodynamic sound source
Δz_{VIB} [m]	Distance from the vibrational source to the microphone in height direction
Δz_{AE} [m]	Distance from the aerodynamic source to the microphone in height direction
l [m]	Distance between infrared sensors at the entrance and exit of the semi-anechoic chamber
x_{i} [m]	Position of the first sensors in rail direction
x_{n} [m]	Position of the second sensors in rail direction
x_{o} [m]	Position of the third sensors in rail direction
x_{t} [m]	Position of the fourth sensors in rail direction
x_{in} [m]	Position of the entrance of the chamber in rail direction
x_{out} [m]	Position of the exit of the chamber in rail direction

V_{in} [m/s]	Velocity of a scaled train model at the entrance of the chamber
V_{out} [m/s]	Velocity of the train model at the exit of the chamber
t_{in} [s]	The time at which the vibrational source passed x_{in}
t_{out} [s]	The time at which the vibrational source passed x_{out}
$\mathbf{r}_{\text{mic}}$	Position vector of the microphone
t_{mic} [s]	The time when the source passed directly under the microphone
$t_{f,\text{source}}$ [s]	The time when a peak frequency of radiated sound from the source is closest to f_{source} at the microphone
x [m]	Position of the vibrational source in rail direction
x_{mic} [m]	Position of the microphone in rail direction
$L_{p,\text{mic}}$ [dB]	SPL of the sources at the microphone
$t_{\text{peak,AE}}$ [s]	The time when the SPL of the aerodynamic source reaches the peak at the microphone
l_{peaks} [m]	Distance which the train model moved from $t_{\text{peak,AE}}$ to $t_{f,\text{source}}$
L_{dir} [dB]	Directivity of the sound radiated from a moving source
α [dB/m]	Air absorption coefficient
ΔL_{source} [dB]	Source term that depends on the directivity characteristics of the source
$\Delta L_{\text{Doppler}}$ [dB]	Motion term that depends on the source's movement
$\Delta L_{\text{conv.}}$ [dB]	Convection term that depends on convection
k [rad/m]	Wave number of radiated sound
r_{panel} [m]	Radius of the panel
J_1	First-order Bessel function of the first kind
$r_{\text{source,eq}}$ [m]	Equivalent radius of the surface of the vibrational source
$\mathbf{r}'_{\text{source}}$	Position vector of an image sound source
$\mathbf{R}'$	Vector from the image source to the microphone
β [rad]	Slope of the nose of the train model

d [m]	Distance from the center of the cylinder of the source to the surface on which the source is attached
ε [rad]	Angle between the direction from the image source to the real source and to the microphone
γ [rad]	Angle between the direction in which the SPL of radiated sound takes the maximum value and the direction perpendicular to the plate to which the aerodynamic source is attached
θ_{peak} [rad]	Angle between source movement and the direction in which the SPL of radiated sound takes the maximum value
P	Order of the multipole ($P = 0, 1$, or 2 for a monopole, dipole, or quadrupole)
$L_{p,w}$ [Pa]	SPL when the wind tunnel works and the aerodynamic source was fixed in the flow
$L_{p,w/o}$ [Pa]	SPL when the wind tunnel works but the aerodynamic source was removed in the flow
r_m [m]	Distance from the source to the microphone (propagation path)
θ_m [rad]	Angle between the direction in which the radiated sound propagates and the flow (propagation angle) when no flow is present
θ_c [rad]	Propagation angle before the refraction
θ' [rad]	Propagation angle after the refraction
$\mathbf{r}_{\text{mic},c}$	Corrected position of the microphone on refraction of a shear layer
$\mathbf{r}_{\text{source},r}$	Retarded position of the cylinder of the aerodynamic source
$\mathbf{r}'_{\text{source},r}$	Retarded position of an image source of the cylinder $\mathbf{r}_{\text{source},r}$
θ_r [rad]	Angle between $\mathbf{r}_{\text{mic},c} - \mathbf{r}_{\text{source},r}$ and the flow
p_{c0p} [Pa]	Corrected sound pressure assuming that a shear layer is planar and that the thickness is sufficiently small compared with the wavelength of the radiated sound
$p_{c\infty p}$ [Pa]	Corrected sound pressure assuming that a shear layer is planar and that the thickness is sufficiently large compared with the wavelength
ζ	Variable related to corrected sound pressure
μ	Variable related to corrected sound pressure

σ	Variable related to corrected sound pressure
h [m]	Distance from the cylinder to the boundary between the potential core and the shear layer in height direction
$L_{\text{dir,dipole}}$ [dB]	Directivity of a dipole on a reflective plate which there is no air flow and the SPL of radiated sound is maximum in the vertical direction

Chapter 5

Symbol	Meaning
m	Infinite straight track
R	Receiver
S_{top}	Top of the source group
S_{end}	End of the source group
S_n	n th source of the source group
x_0 [m]	x -coordinate of R
y_0 [m]	y -coordinate of R
r [m]	Distance from the track to R
N	Number of point sources that compose the sound source group
L [m]	Length of the source group
z_{S_n} [m]	z -coordinate of S_n
z_n [m]	z -coordinate of S_n at $t = 0$
a [m ³ /s]	Sound signal (volume velocity) from each source
$\tilde{a}$ [m ³ /s]	amplitude of a
p_n [Pa]	Sound pressure radiated from S_n
$p_{A,n}$ [Pa]	A-weighted sound pressure from S_n
p_A [Pa]	A-weighted instantaneous sound pressure from the entire source group
$\bar{p}_n$ [Pa]	RMS value of p_n
$\bar{p}_{A,n}$ [Pa]	RMS value of $p_{A,n}$
$\bar{p}$ [Pa]	RMS value of the sound pressure from the entire source group
$\bar{p}_A$ [Pa]	RMS value of the A-weighted pressure from the entire source group
ϕ_n [m ² /s]	Velocity potential of S_n
$\delta(x)$	Dirac delta function of x
Φ_n	Fourier-transform of ϕ_n with respect to t and z

$A_{xy,n}$	Fourier-transform of $a(t) \exp(-ik_z z_{S_n})$ with respect to t
$\Phi_{xy,n}$	Φ_n where $A_{xy,n} = 1$
k_{xy} [rad/m]	Wavenumber in perpendicular direction to z -axis
A	Fourier transform of a with respect to t
$H_0^{(1)}$	0th-order Hankel function of the first kind
k'_z	Variable related to integral transform
u	Variable related to integral transform
v	Variable related to integral transform
k'_z	Variable related to integral transform
K	Certain real number
κ	Integral variable
r'	$= \sqrt{(1 - M^2) r^2 + (-z_n - Vt)^2}$
φ	Phase of ϕ_n
ω'_n	Frequency of radiated sound from S_n
ω_n	Frequency of the radiated sound from S_n if the change of azimuth angle of R as seen from S_n is ignored during the time that it takes from the sound propagation from S_n to R
f'_n [Hz]	$\omega'_n/2\pi$
f_1 [Hz]	20.60 Hz
f_2 [Hz]	107.7 Hz
f_3 [Hz]	737.9 Hz
f_4 [Hz]	12,194 Hz
L'_A [dB]	A-weighted SPL radiated from the entire source group considering source movement
L_A [dB]	A-weighted SPL radiated from the entire source group ignoring source movement
ΔL_A [dB]	Level difference between L'_A and L_A
p_0	20 μ Pa

L_{AS} [dB]	A-weighted SPL with time weighting S (slow)
p_{AS} [Pa]	A-weighted instantaneous sound pressure related to L_{AS}
τ_S [s]	Time constant for time weighting S (slow)
ξ	Dummy variable of time integration
Δt [s]	Time step
$L_{Aeq,T}$ [dB]	Time-averaged sound level, or equivalent continuous sound level
T [s]	Measurement time interval
t_1 [s]	Beginning time of T
t_2 [s]	Ending time of T
$L_{A,n}$ [dB]	A-weighted instantaneous SPL of S_n
d_n [m]	Distance between S_n and R
L_{wA} [dB]	A-weighted PWL of a single sound source of the source group
L_w [dB]	PWL of the single source
$L_{p,n}$ [dB]	SPL of S_n
L_p [dB]	SPL of the entire source group
$L_{\max}$ [dB]	Maximum SPL
$L_{S\max}$ [dB]	Maximum SPL with time weighting S (slow)
$L_{eq,Tp}$ [dB]	Time-averaged SPL on the pass-by time
$L_{A\max}$ [dB]	Maximum A-weighted SPL
$L_{AS\max}$ [dB]	Maximum A-weighted SPL with time weighting S (slow)
$L_{Aeq,Tp}$ [dB]	A-weighted equivalent continuous sound pressure level on the pass-by time
T_p [s]	Pass-by time
$N_{\exp}$	Noise speed exponent

Chapter 1

Introduction

1.1 Background

1.1.1 Transportation noise prediction

Since the Industrial Revolution, numerous machines have been invented and widely disseminated worldwide, leading to an overflow of various types of noise in human living environments. Under such circumstances, continuous exposure to noise has been found not only to cause discomfort to individuals but also to increase health risks such as cardiovascular diseases, cognitive impairment in children, sleep disturbances, tinnitus, and other adverse effects on the human body. For example, in 2011, the WHO Regional Office for Europe estimated that the total loss of life years (disability-adjusted life years, DALY) due to environmental noise in Western European countries amounted to approximately 1.6 million years [1]. Consequently, environmental noise has increasingly been recognized as a health risk factor in many countries around the world in recent years. In 2018, the WHO Regional Office for Europe published the Environmental Noise Guidelines for the European Region [2], which provide recommended exposure levels for various types of noise (Table 1.2). Here, L_{den} , L_{night} , and $L_{\text{Aeq},24\text{h}}$ [dB] represent the day-evening-night equivalent sound level, night equivalent sound level, and 24-hour equivalent sound level, respectively.

In line with this trend, noise distribution estimates over extensive areas are being conducted worldwide, similar to the establishment of environmental standards for noise. In the EU, the Environmental Noise Directive (END) [3] was issued in 2002, mandating member states to create and publish strategic noise maps (large-scale noise exposure contour maps) every five years for

Table 1.1: Disability-Adjusted Life Year (DALY) by environmental noise in Western Europe [1].

Health effects	DALY [years]
Ischaemic heart disease	61,000
Cognitive impairment of children	45,000
Sleep disturbance	903,000
Tinnitus	22,000
Annoyance	654,000
Total	About 1,600,000

Table 1.2: Recommended noise levels by Environmental noise guidelines for the European region [2].

Noise source	L_{den} [dB]	L_{night} [dB]
Road traffic noise	53	45
Railway noise	54	44
Aircraft noise	45	40
Wind turbine noise	45	n.a.
Leisure Noise	70 ($L_{\text{Aeq},24\text{h}}$)	

- agglomerations with more than 100 000 inhabitants
- major roads (more than 3 million vehicles a year)
- major railways (more than 30 000 trains a year)
- major airports (more than 50 000 take-offs or landings a year, including small aircrafts and helicopters)

based on sound source data and propagation calculations. As a result, noise maps for various sources have been produced across Europe four times to date: in 2007, 2012, 2017, and 2022. As an example of the public noise map for noise sources such as automobiles, railways, aircraft in Europe, The NOISE Observation & Information Service for Europe by European Environment Agency [4] is shown in Fig. 1.1. This figure shows L_{den} and L_{night} [dB] of the railway noise in the Europe.

Similarly, in the United States, the U.S. Department of Transportation's Bureau of Transportation Statistics released National Transportation Noise Map [5] in 2017 [6],

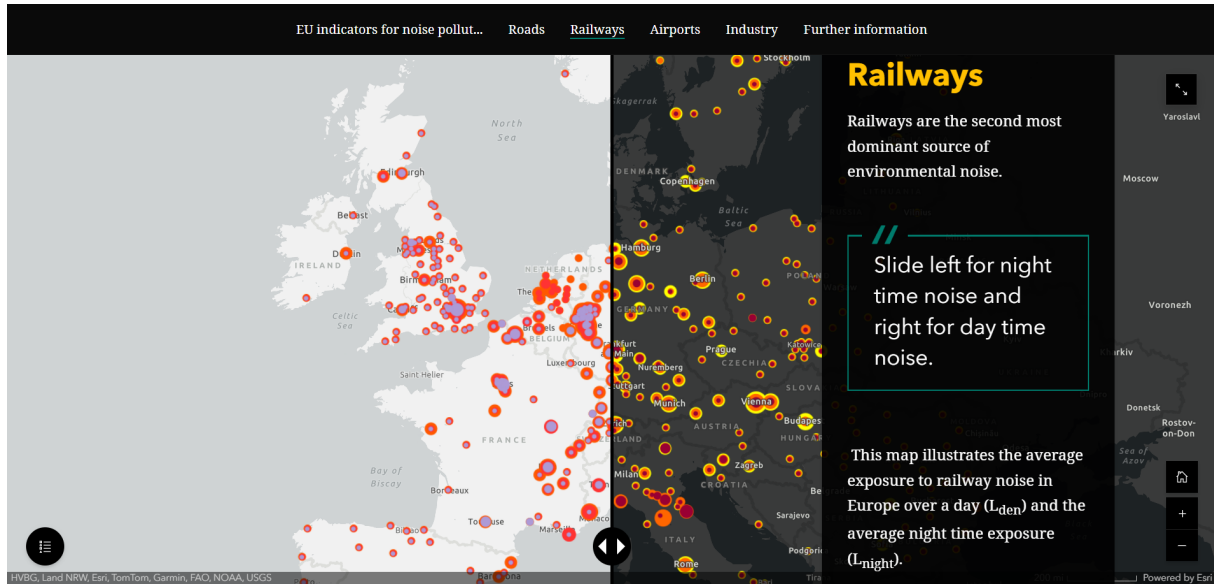


Figure 1.1: The NOISE Observation & Information Service for Europe by European Environment Agency [4].

which is a nationwide transportation noise map showing noise sources such as automobiles, railways, and aircraft. Figure 1.2 represents $L_{Aeq,24h}$ [dB] for railway noise in Chicago, the United States from the map.

An example of such a noise map in Japan, showing road traffic noise in Osaka City, Japan [7], is presented in Fig. 1.3 representing $L_{Aeq,24h}$ [dB].

In urban areas, major sources of noise include transportation noise generated by automobiles, railways, and aircraft. For example, in Europe, buildings are often densely clustered in towns or cities while structures are sparse in other areas. Conventional railways are constructed to connect stations in these towns and cities, where existing conventional railway lines are being upgraded for high-speed travel, allowing both high-speed and conventional trains to share the same tracks. High-speed trains that stop only at major cities pass through small settlements at high speeds, potentially causing noise problems similar to those in Japan. Since local governments in Europe have significant authority over urban planning, it is necessary to avoid constructing residential buildings in areas predicted to experience high noise levels through analysis, thereby reducing the population exposed to noise. For high-speed trains like the Shinkansen and the Chuo Shinkansen in Japan, efforts are being made to improve running speeds to enhance convenience as environmentally friendly public transportation systems. As running speeds

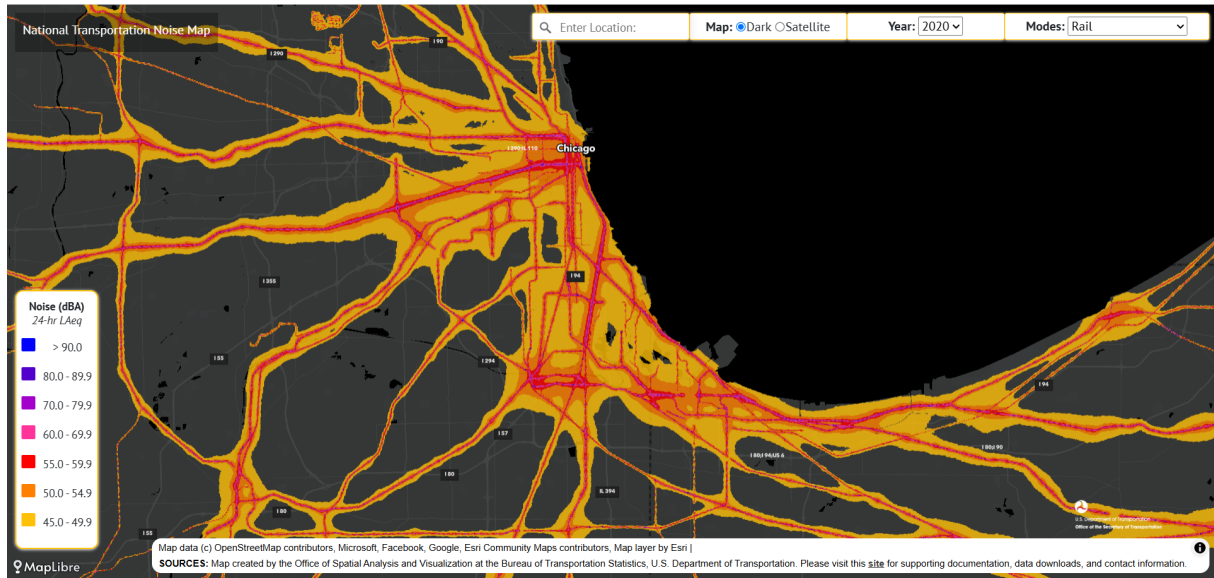


Figure 1.2: A noise map for railway noise in Chicago, the United States [5].

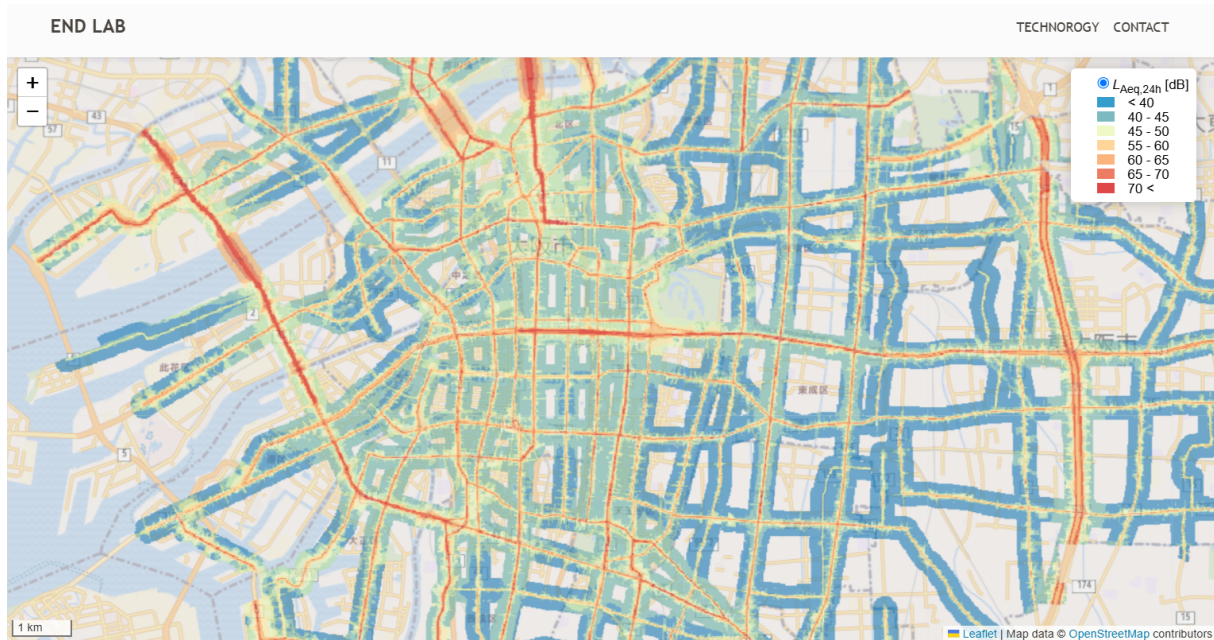


Figure 1.3: A noise map for road traffic noise in Osaka City, Japan [7].

increase, noise exposure for nearby residents also rises, prompting railway operators and vehicle manufacturers to strive for quieter railway vehicles. Under such circumstances, it is necessary to investigate the changes in noise propagation characteristics caused by the high-speed movement of railway vehicles and noise maps play an extremely important role.

Therefore, noise prediction methods or frameworks for transportation noise (e.g., Harmonoise [8] and CNOSSOS-EU [9] in Europe, ASJ RTN-Model [10], a noise prediction method for conventional railways [11], and the method for the Shinkansen [12] in Japan) have been developed and released for several decades. However, they assume that the speeds of vehicles are negligibly low compared with the sound speed on evaluating the transportation noise levels, neglecting the effect of frequency modulation (Doppler effect) and amplitude modulation of radiated sound from vehicles, which occur when sound sources move. They lack any correction term considering the modulations induced by source movement even for high-speed vehicles such as the Shinkansen, which pass through residential areas at approximately 0.1 to 0.3 times the speed of sound.

Especially in the case of railway noise in Japan, more than 20 years have passed since railway noise prediction models were proposed [11,12], and it is no longer compatible with the latest high-speed rolling stock. Furthermore, due to past lawsuits filed by residents living along railway lines regarding railway noise in the mid-1970s, measured data of operating trains has not been made publicly available. As a result, the sound source models used in existing noise prediction methods have not been sufficiently verified for railway noise.

1.1.2 Beamforming

In order to localize noise sources that require to be reduced or to verify the effectiveness of noise reduction, beamforming has been frequently conducted by phased microphone array measurements. Especially, Delay and Sum beamforming (DAS) [13] has been widely used for sound source localization and quantification of radiated sound power for the past several decades. Figure 1.4 illustrates the schematic of DAS [14]. A scanning plane which is moving along a sound source (an aircraft in the figure) is assumed. A grid is depicted on the scanning plane and a point source is assumed on each grid point $\mathcal{F}$. Then each point is focused and equivalent amplitude (beamforming output) of the source on the point is determined using measured sound pressures by each microphone $\mathcal{M}$. Thus a

contour map representing the source distribution is depicted on the scanning plane using the determined amplitudes of all the point sources as shown in the figure. However, the conventional DAS cannot locate and quantify the moving sound sources because there is frequency modulation by Doppler effect on the sound pressure wave measured at each microphone.

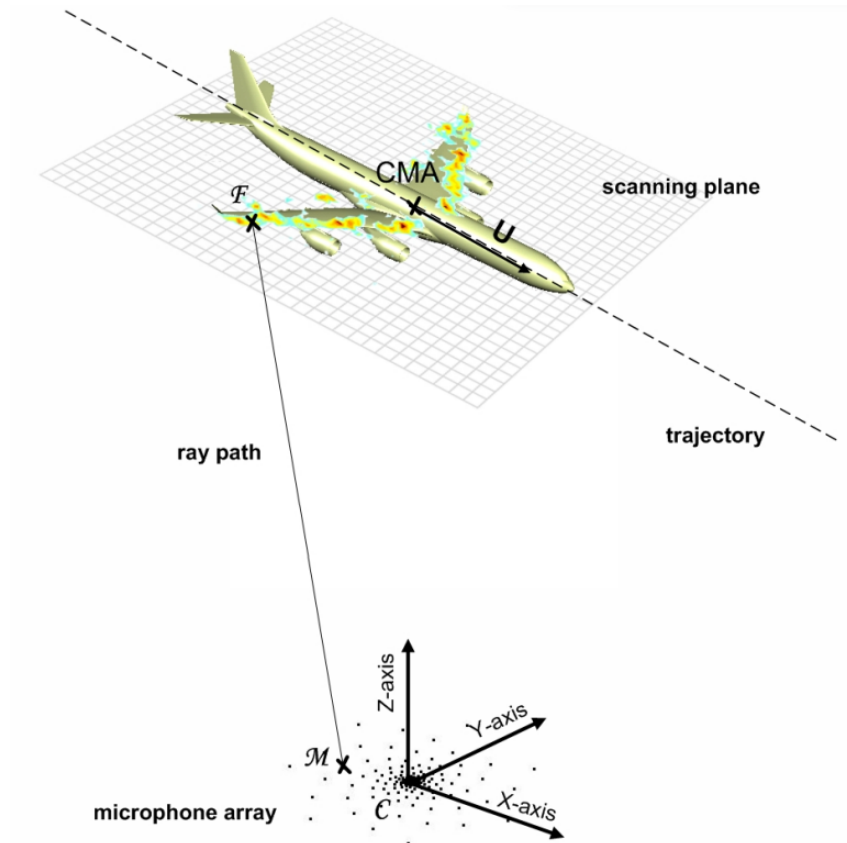


Figure 1.4: The schematic of Delay and Sum beamforming (DAS) [14].

Thus, the sound pressure measured by microphones are traced back to the signals of a target moving source by removing the Doppler effect (de-Dopplerization), which is removed by resampling the original time series by linear interpolation [15] for instance. The conventional beamforming is then applied on the de-Dopplerized signals. Beamforming with de-Dopplerization has been applied to the location of transportation noise in straight-line motion, such as the train pass-by noise [16, 17], the aero plane fly-over noise [15, 18–20], and pass-by tests on railway high speed trains [21, 23, 24].

The deconvolution algorithms (e.g., CLEAN [25], DAMAS [26], and the extensions [27–

[32] of them to fulfill the tasks of fast computing, separation of coherent sources and other adaptive capabilities are also developed for the conventional beamforming which suffers from the low spatial resolution and inaccurate interpretation of source location. The algorithms are conventionally operated in the frequency domain, whereas the de-Dopplerization is generally processed in the time domain. On the other hand, Guerin *et al.* [33] proposed an approximate Point Spread Function (PSF) in the frequency domain for a moving source, assuming that the acoustic energy of a broadband source is equally exchanged between neighboring frequency bands. This approach worked well for the broadband noise but failed to identify the tonal sources. Thus they [14] also proposed the modification of the PSFs due to source movement, which was validated by real tests of Airbus A340 flyovers [34]. This method is a hybrid time-frequency approach because beamforming is applied in the time domain while the PSFs used in DAMAS are computed in the frequency domain. Haldet *et al.* [35] proposed a different method from their method to formulate a Doppler corrected PSF but yielded similar results. The approach was applied to fly-over measurements taken on an MU300 business jet. Fleury *et al.* extended several deconvolution approaches to locate the moving sources at low-Mach speed by using the conventional Doppler frequency shift approximation [36]. The approaches were used to assess the slat noise from Airbus A340 [37].

Recently, beamforming has been conducted for the mapping and estimating sound power levels or directivities of each component of vehicles to acquire sound source models for noise prediction models. For example, noise prediction framework named J-FRAIN was developed and published for the precise prediction of aircraft noise around airports without referencing undisclosed technical information of each component of aircrafts [38–40]. In the framework, only the Doppler effect due to the movement of the source (piling-up process of flux between a moving source and observer [41]) is considered in both sound source and sound propagation models. Then the differences of amplitude modulation of each component of the moving aircrafts are included as a part of the directivities in the source models [39]. However, the change of the directivities of the source models remains unclear.

1.2 Purpose

It is well known that frequency modulation (Doppler effect) and amplitude modulation occur in the radiated sound due to sound source movement. However, lots of aspects of the acoustic propagation characteristics associated with moving sound sources remain unclear. Especially, there are few studies that have clarified the effects of these phenomena on radiated sound characteristics or on noise evaluation.

As a result, the effect of these changes on the characteristics of radiated sound is often neglected. In transportation noise estimation or prediction methods generally assume that the sound propagation is much faster than the source velocity. This is especially true in cases where multiple sound sources, such as vehicles in high-speed railways like the Shinkansen trains, travel at speeds of several hundred kilometers per hour, and pass through residential areas at speeds equivalent to approximately 0.1 to 0.3 times the speed of sound. Despite that the assumption does not strictly hold in such cases, prediction methods neglecting the speed of moving source are widely used for transportation noise estimation.

This dissertation aims to clarify the extent to which noise metrics of current noise prediction models or frameworks are underestimated by neglecting the frequency and amplitude modulation induced by source movement, and under what conditions such underestimations are more significant. Then it also aims to clarify what factors other than source speed affect the degree of this underestimation, which need to be taken into account for improved noise prediction models considering source movement.

At first, amplitude modulation of radiated sound caused by source movement are exemplified for different types of point sound sources and the relationships among the sources. Then the differences of amplitude modulation due to the movement of different types of sound sources are clarified experimentally. After that, the differences between amplitude modulations induced by source movement and convection which occurs in a wind tunnel is clarified with a wind tunnel experiment. Additionally, transportation noise source is simplified as a point source group, and the effects of frequency and amplitude modulation caused by the source movement along a straight track are examined in terms of their impact on evaluation of noise metrics (the peak or mean value in energy of A-weighted sound pressure levels) used in transportation noise prediction.

In this dissertation, change of amplitude of radiated sound induced by source move-

ment and convection is expressed as "amplitude modulation". It is true that the term is commonly understood as a mechanism in which the amplitude of a carrier wave is varied according to the signal waveform when transmitting a signal in the fields of engineering and science and is exemplified by the operating principle of ultrasonic speakers in the field of acoustics. However, since changes of frequency of radiated sound due to the Doppler effect are often referred to as the term "frequency modulation" (e.g., [42–48]), changes of amplitude of radiated sound are expressed as "amplitude modulation" accordingly. Then Mach numbers below 0.3 are defined as low Mach numbers, where change in fluid density is less than 5% [49]. The studies in this dissertation focused on sound sources moving within the low Mach number range.

1.3 Structure of the dissertation

Figure 1.5 shows the outline of the dissertation. The rest of this dissertation is organized as follows.

Chapter 2 introduces frequency modulation due to Doppler effect and the dimensionless quantity Doppler factor. Then it describes the relationship of the factor due to source movement and change of apparent wavelength of radiated sound induced by convection. After that it explains the reason why amplitude modulation of the radiated sound by source movement and that by convection can be compared using Doppler factor or the ratio of apparent wavelength to the wavelength at the pulsation frequency of the source.

Chapter 3 reveals how the sound source types affect the amplitude modulation of radiated sound from the vibrational and aerodynamic sound source because of source movement with the scaled train model experiment.

Chapter 4 reveals the influence of source movement or convection on the amplitude of radiated aerodynamic sound by explaining the wind tunnel experiment and comparing the result with the results in Chapter 3.

Chapter 5 explains the investigation of the effects of frequency and amplitude modulation caused by sound source movement on radiated sound characteristics of a sound source group moving at constant velocity by calculating A-weighted sound pressure level. The level is calculated as the energy sum of the radiated sound from each moving source of the group. Sound pressure from each source is calculated based on the analytical solution in Chapter 2 and verified experimentally as a vibrational sound source in Chapter 3.

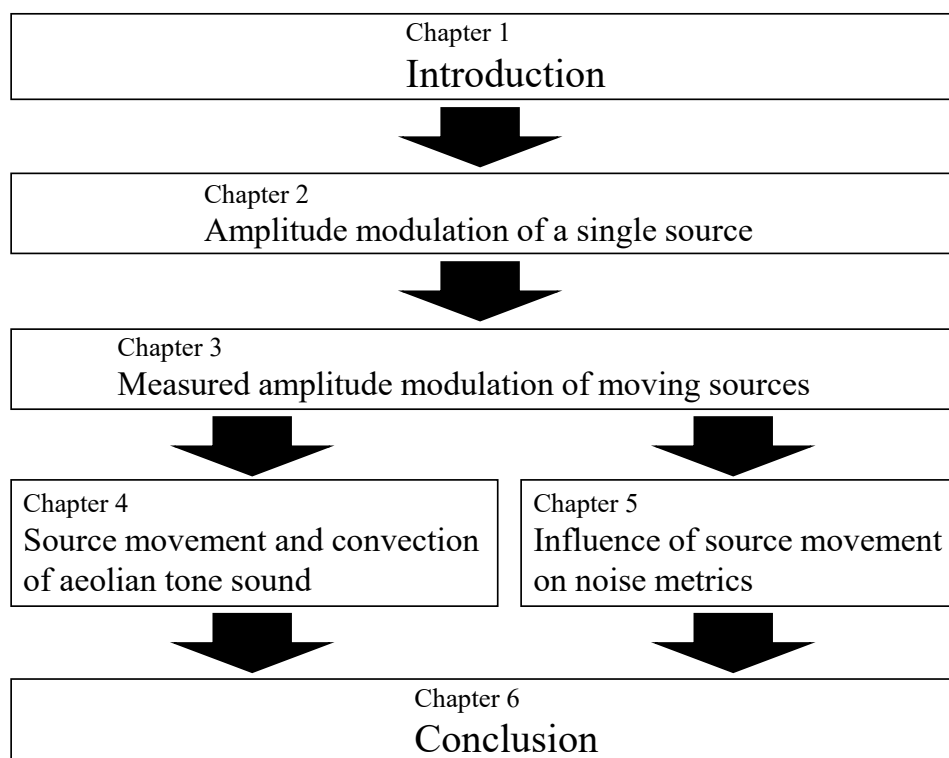


Figure 1.5: Outline of this dissertation.

Especially the chapter clarifies the effect of the modulations on three kinds of A-weighted sound pressure levels appeared in transportation noise prediction.

Finally, Chapter 6 provide conclusions of this entire dissertation and exemplifies several future issues.

Chapter 2

Amplitude modulation of a single source

2.1 Introduction

In this chapter, frequency modulation (Doppler effect) and amplitude modulation is introduced. At first, Doppler factor is defined as dimensionless quantity related to the frequency modulation. Then analytical solutions of radiated sound pressure from a moving point source are exemplified for the sources with various physical mechanisms. For example, Morse and Ingard [50] derived the analytical solution of amplitude modulation of radiated sound from a monopole sound source moving at constant velocity. Howe [51] described analytical solutions for sound radiated from a moving monopole, dipole, and quadrupole of an aerodynamic source. Representing the analytical solutions, the relationship between frequency and amplitude modulation of the analytical solutions is discussed.

On the other hand, wind tunnel experiments have been conducted to measure or to evaluate an aerodynamic sound caused by a vehicle instead of a measurement of the sound in a field test or a train model launching experiment from vehicles actually moving in the stationary air. From the reason, the frequency and amplitude modulation due to convection is explained and compared with the modulations due to source movement.

2.2 Frequency of radiated sound from a moving source

As shown in Fig. 2.1, a single source moving at velocity vector $\mathbf{V}(t)$ on a straight track is assumed; t [s], $\mathbf{r}_{\text{source}}(t)$, and $\mathbf{r}_{\text{mic}}$ denote time, the position of the center of the source, and the position of a stationary microphone, respectively.

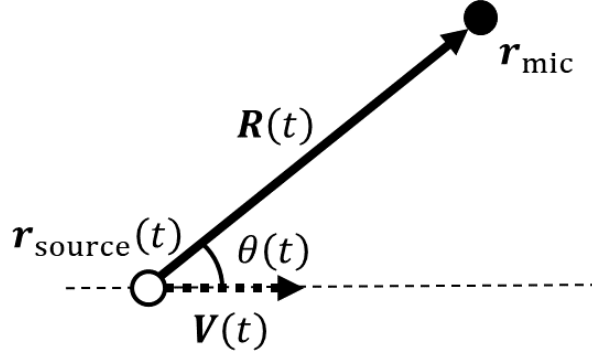


Figure 2.1: A moving source $\mathbf{r}_{\text{source}}(t)$ at velocity vector $\mathbf{V}(t)$ and a microphone $\mathbf{r}_{\text{mic}}$.

An angle $\theta(t)$ [rad] between $\mathbf{V}(t)$ and the vector which represents the propagation path $\mathbf{R}(t)$ of sound radiated at time t from the source to the microphone is expressed as

$$\theta(t) = \arccos \left(\frac{\mathbf{R}(t) \cdot \mathbf{V}(t)}{|\mathbf{R}(t)| |\mathbf{V}(t)|} \right), \quad (2.1)$$

where

$$\mathbf{R}(t) = \mathbf{r}_{\text{mic}} - \mathbf{r}_{\text{source}}(t). \quad (2.2)$$

The radiated frequency from the source f [Hz] can be derived as

$$f = f_{\text{source}} D_f, \quad (2.3)$$

where f_{source} [Hz] is the pulsation frequency of the sound source and D_f is the Doppler factor [51] representing the ratio of f to f_{source} , which is expressed using the velocity $V(=|\mathbf{V}|)$ [m/s] and the speed of sound c [m/s] as

$$D_f = \frac{1}{1 - M \cos \theta} \quad (2.4)$$

where $M(=V/c)$ is the Mach number.

Note that sound wave emitted at the time t from the moving source reaches the microphone at the time $t + R/c$ where $R(=|\mathbf{R}|)$ [m] is propagation path from the source to the microphone or an any other observer.

2.3 Amplitude modulation of moving sources with various physical mechanisms

In the absence of mean flow and dissipation, inhomogeneous wave equation describing the production of sound waves can be expressed as [51]

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \rho \frac{\partial \bar{q}}{\partial t} - \text{div} \bar{\mathbf{F}} \quad (2.5)$$

where p [Pa] is sound pressure; ρ [kg/m³] is air density; $\bar{q}$ [/s] and $\bar{\mathbf{F}}$ are the rate of increase of fluid volume and the localized body force applied to the fluid per unit volume of the fluid. It will often be convenient to replace the right side of the equation by a generalized pressure source $\mathcal{F}$ [Pa/m²] and to write

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \mathcal{F}. \quad (2.6)$$

Here, the analytical solutions of radiated sound pressure from a moving point source at a constant velocity V is exemplified.

At first, a monopole point source (pulsating sphere) is introduced as shown in Fig. 2.2. Radiated sound from the source is generated either by injecting or withdrawing fluid from the propagating medium, or by expanding or contracting a closed impermeable boundary surface [41]. This source can be regarded as a simplified vibrational sound source such as a speaker or a car body because sound waves are emitted by vibrating the surface of the source in the normal direction.

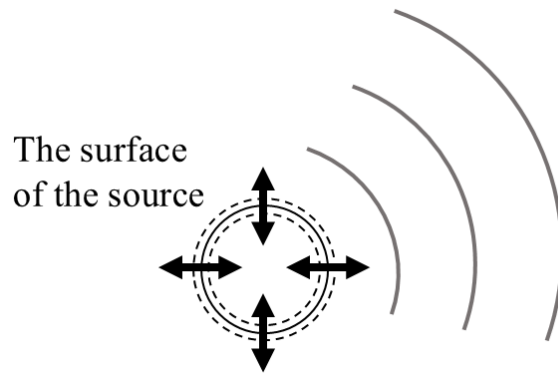


Figure 2.2: A monopole point source (pulsating sphere).

When the source is moving, $\bar{\mathbf{F}} = 0$ and $\bar{q}$ is expressed as

$$\bar{q} = q(t) \delta(\mathbf{r} - \mathbf{r}_{\text{source}}(t)) \quad (2.7)$$

where $q(t)$ [m³/s] is the volume velocity of the point source and $\mathbf{r}$ is the position vector of an observer. Substituting Eq. (2.7) and $\bar{\mathbf{F}} = 0$ into Eq. (2.5) and integrating both sides of Eq. (2.5) with respect to t , the wave equation of velocity potential ϕ [m²/s] is written as

$$\frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} - \nabla^2 \phi = q(t) \delta(\mathbf{r} - \mathbf{r}_{\text{source}}(t)), \quad (2.8)$$

which is derived using the relationship as

$$p = \rho \frac{\partial \phi}{\partial t}. \quad (2.9)$$

Then ϕ of the moving source is derived as [50]

$$\phi(t) = \frac{q \left(t - \frac{R}{c} \right)}{4\pi R (1 - M \cos \theta)}. \quad (2.10)$$

Note that for the various analytical solutions of radiated sound from a moving point source, the variables R , θ , and M in this section is not evaluated at the reception time t but the emission time τ [s], which means the time when the sound is emitted from the source and satisfies that

$$\tau + \frac{R(\tau)}{c} = t. \quad (2.11)$$

Sound pressure p [Pa] from the moving source is derived as [50]

$$p(t) = \frac{\rho q' \left(t - \frac{R}{c} \right)}{4\pi R (1 - M \cos \theta)^2} + \frac{\rho q \left(t - \frac{R}{c} \right) V (\cos \theta - M)}{4\pi R^2 (1 - M \cos \theta)^3}. \quad (2.12)$$

The second term of the right side is near-field term and can be neglected in the far-field. The amplitude difference with and without the term is less than 0.1 dB when the observer is at 7.5 m from the line of motion of the source [52]. Then p can be approximated as [50, 51]

$$p(t) \approx \frac{\rho q' \left(t - \frac{R}{c} \right)}{4\pi R (1 - M \cos \theta)^2}, \quad (2.13)$$

where $q'(t) (= \partial q / \partial t)$ is the time derivative of $q(t)$, suggesting that the pressure is approximately proportional to the second power of the Doppler factor assuming that the numerator of the right side of Eq. (2.13) is constant.

Secondly, a dipole component of an aerodynamic sound is introduced which is generated by pressure fluctuation. As the simplified sound source of that, Figure 2.3 illustrates the cross section of a cylinder in air flow perpendicular to the cross section. A free-stream aeolian tone is generated from pressure fluctuation on the surface of the cylinder induced by turbulence around the cylinder. Then the aeolian tone has the dipole directivity. The cylinder also generates periodic Karman vortex shedding in the wake from the cylinder.

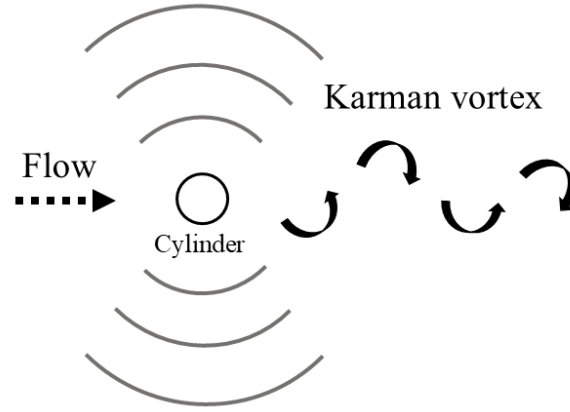


Figure 2.3: Cross section of a cylinder in air flow generating an aeolian tone as a simplified dipole component of an aerodynamic sound.

Provided that changes in air density and pressure are sufficiently small compared with mean air density and atmospheric air pressure. When an external force is acting on a moving point source, $\bar{\mathbf{F}}$ can be represented as

$$\bar{\mathbf{F}} = \mathbf{F}\delta(\mathbf{r} - \mathbf{r}_{\text{source}}(t)) \quad (2.14)$$

where $\mathbf{F}$ is the external force acting on the point source. Substituting Eq. (2.14) and $\bar{q} = 0$ into Eq. (2.5), $p(t)$ [Pa] of fluid-generated sound from the source in the far field is expressed as [51]

$$p(t) \approx \frac{F'_j \left(t - \frac{R}{c} \right) \cos \theta_j}{4\pi c R (1 - M \cos \theta)^2} \quad (2.15)$$

where $F_j(t)$ [N] is the external force on the point source and subscript j denotes the component in the direction of each axis in the three-dimensional Cartesian coordinates (i.e., $j = 1, 2, 3$ correspond to the x, y, z axes, respectively); $F'_j(t)$ ($= \partial F_j / \partial t$) is the time derivative of F_j ; θ_j [rad] is an angle between the propagation direction of the radiated

sound and each axis. This is sum of the pressure of the three dipole sources which correspond to different axes. Assuming that the numerator of the right side of Eq. (2.15) is constant, p is approximately proportional to the second power of D_f .

Thirdly, a quadrupole component of aerodynamic sound is explained, which is generated from the turbulence or flow distortion of fluid such as jet from a nozzle as shown in Fig. 2.4.

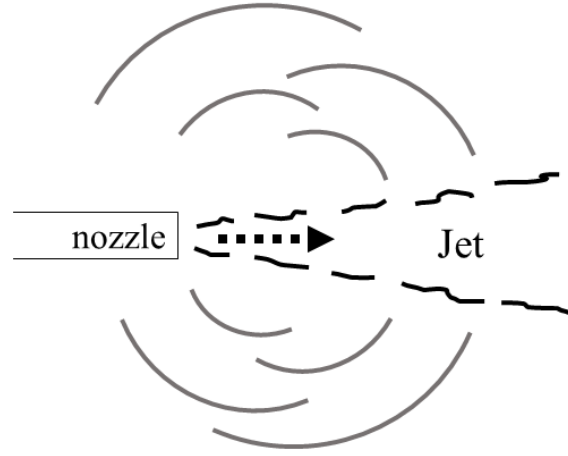


Figure 2.4: Jet from a nozzle radiating a quadrupole component of an aerodynamic sound.

Although it is generally not permissible to assume that the turbulent flow is compact [51], when a simplified moving sound source radiating the quadrupole component is defined, $\mathcal{F}$ in Eq. (2.6) is represented as

$$\mathcal{F} = \frac{\partial^2(t_{ij}\delta(\mathbf{r} - \mathbf{r}_{\text{source}}(t)))}{\partial x_i \partial x_j} \quad (2.16)$$

where t_{ij} [N · m] is the element of turbulence stress tensor. $p(t)$ [Pa] is approximated as [51]

$$p(t) \approx \frac{t''_{ij} \left(t - \frac{R}{c}\right) \cos \theta_i \cos \theta_j}{4\pi c^2 R (1 - M \cos \theta)^3} \quad (2.17)$$

where $t''_{ij} = \partial^2 t_{ij} / \partial t^2$. θ_i [rad] is an angle between the propagation direction of the radiated sound and each axis as well as θ_j (i.e., $i = 1, 2, 3$ correspond to the x, y, z axes, respectively). Assuming that the numerator of the right side of Eq. (2.17) is constant, p is approximately proportional to the third power of D_f .

Additionally, the analytical solution of radiated pressure of a moving point source is also derived for a pressure point source [51] as an ideal sound source, which is expressed as

$$\mathcal{F} = S(t)\delta(\mathbf{r} - \mathbf{r}_{\text{source}}(t)) \quad (2.18)$$

where $S(t)$ [kg/s²] is the source strength. Substituting this into Eq. (2.5), p is derived as

$$p(t) = \frac{S\left(t - \frac{R}{c}\right)}{4\pi R(1 - M \cos \theta)}, \quad (2.19)$$

suggesting that it is proportional to D_f assuming that the numerator of the right side is constant.

From the sound pressure of all of the moving point sources mentioned above, amplitude modulation of radiated sound from a moving point source can be expressed as powers of D_f by source movement. Therefore, amplitude modulation of the radiated sound by source movement can be compared using the Doppler factor D_f .

Especially, note that the exponent of the sound pressure of the pulsating sphere is 1 larger than that of the pressure point source because of a time derivative process as in Eq. (2.9) while solving sound pressure p in Eqs. (2.6) and (2.18) is equivalent to solving velocity potential ϕ in Eq. (2.8).

2.4 Modulated wavelength and amplitude modulation due to convection

The wavelength of radiated sound from a moving source is inversely proportional to the radiated frequency or the Doppler factor when c is constant. The ratio of the wavelength of radiated sound λ [m] to the wavelength of the sound $\lambda_{\text{source}} (= c/f_{\text{source}})$ [m] when $V = 0$ can be written as

$$\frac{\lambda}{\lambda_{\text{source}}} = \frac{1}{D_f} = 1 - M \cos \theta. \quad (2.20)$$

On the other hand, in a wind tunnel experiment, sound sources are usually fixed in the air flow inside a wind tunnel when radiated sound is measured as the stationary sound. Here, a stationary sound source and a stationary microphone are assumed in a steady flow with the velocity $\mathbf{V}_{\text{flow}}$. In the flow, the frequency modulation (Doppler effect) does not occur because the sources and microphones are stationary. However, because of

convection, the apparent sound speed from the viewpoint of a stationary observer differs by propagation direction from the source. Thus, the apparent wavelength also differs by the direction. This is a phenomenon common to the case in which the sound source is physically moving and the air is stationary, and the case in which the source is stationary and the air. As shown in Fig. 2.5, from the viewpoint of an observer moving with the air flow, a sound source is moving in the opposite direction and at the same velocity as the flow ($= -\mathbf{V}_{\text{flow}}$). The ratio of the apparent wavelength λ of the radiated sound to the wavelength λ_{source} when flow velocity $V_{\text{flow}} (= |\mathbf{V}_{\text{flow}}|) = 0$ [m/s] is expressed as

$$\frac{\lambda}{\lambda_{\text{source}}} = 1 - M_{\text{flow}} \cos \theta, \quad (2.21)$$

where $M_{\text{flow}} (= V_{\text{flow}}/c)$ is the Mach number of the flow and θ is an angle between $\mathbf{R}$ and $-\mathbf{V}_{\text{flow}}$.

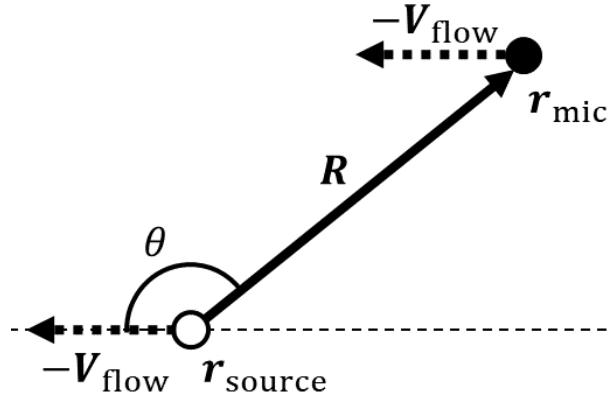


Figure 2.5: A sound source $\mathbf{r}_{\text{source}}(t)$ and a microphone $\mathbf{r}_{\text{mic}}$ in a flow at velocity $\mathbf{V}_{\text{flow}}$ from the viewpoint of an observer moving with the air flow.

Therefore, the spatial expansion or contraction of the apparent wavelength of the radiated sound due to the Mach number of the sound source or the air flow is a phenomenon common to both source movement and convection. $\lambda/\lambda_{\text{source}}$ represents the expansion and contraction of the apparent wavelength as seen by an observer moving with the air flow.

According to the previous section, amplitude modulation of radiated sound from a moving point source can be expressed as powers of D_f by source movement. This indicates that amplitude modulation of radiated sound can be expressed as powers of $\lambda/\lambda_{\text{source}}$ by convection as well as source movement. For example, assuming that the numerator of the right side of Eqs. (2.15)(2.17) is constant, p is inversely proportional to the second and

third power of $\lambda/\lambda_{\text{source}}$ from Eq. (2.20). Therefore, amplitude modulation of the radiated sound by source movement and that by convection can be compared using $\lambda/\lambda_{\text{source}}$.

2.5 Summary

Frequency and amplitude modulation of a moving point source or a point source fixed in the air flow is introduced. For a moving point source, Doppler factor is defined as the ratio of frequency of radiated sound at a receiver to the pulsation frequency of the source. All of the analytical solutions are expressed as a power of the Doppler factor while the exponent of the sound pressure depends on the physical mechanism of the source. When a sound source is fixed in air flow, the ratio of apparent wavelength of radiated sound to the wavelength of the sound at the pulsation frequency of the source represents the expansion and contraction of the apparent wavelength as seen by an observer moving with the air flow and is reciprocal of Doppler factor when the source is moving in the stationary air. Therefore, the spatial expansion or contraction of the apparent wavelength of the radiated sound due to the Mach number of the sound source or the air flow is a phenomenon common to both source movement and convection. Because sound pressure or intensity of radiated sound in the farfield from moving point sources or sources fixed in the air flow are expressed as powers of the Doppler factor or the ratio, amplitude modulation of the radiated sound by source movement and that by convection can be compared using Doppler factor or the ratio.

Chapter 3

Measured amplitude modulation of moving sources

3.1 Introduction

In the previous chapter, the variation in directivity of a single sound source due to amplitude modulation caused by its movement was presented.

Based on the analytical solutions in the chapter, radiated sound pressures of moving sources have been modeled on many studies. For instance, convective amplification of radiated sound pressure due to source movement is frequently corrected in de-Dopplerization during beamforming introduced in Section 1.1.2 as well as distance attenuation and time distortion (Doppler effect) of the radiated sound. The convective amplification of each point source on a scanning plane (see Section 1.1.2) have been assumed to be

1. the second power of D_f , which corresponds to Eq. (2.13) [30, 52–58]
2. the first power of the Doppler factor D_f , which corresponds to Eq. (2.19) [18, 35, 36, 59, 60]
3. neglected, where the radiated sound pressure is not proportional to D_f [14, 21, 22, 33, 61, 62]

in computing beamforming output at the point sources. For another sound source localization method than beamforming, there are studies which the sound pressure of each point source is assumed to be proportional to the second power of the Doppler factor and the near-field term is not neglected, which corresponds to Eq. (2.12) [63, 64]. For the different convective amplifications, Camier *et al.* [65] compared three kinds of Delay and

Sum beamforming algorithms considering different convective amplifications which are exemplified above. They revealed that the misleading de-Dopplerization method results in errors in term of absolute quantification, evolution of the instantaneous amplitude of the recovered source signal, and estimation of the directivity pattern and show significant cumulative errors for the high-speed motion on the beamforming maps.

Besides the studies on sound source localization, the sound pressure of a moving point source has been assumed to be

- proportional to the second power of D_f , which corresponds to Eq. (2.13) [66]
- proportional to the second power of the Doppler factor and the near-field term is not neglected [67]

in the studies on sound source modeling for simulations of sound propagation.

There are some analytical studies related to amplitude modulation of moving sources as well as the studies mentioned in the previous chapter. Dowling [68] investigated a sound radiated from a pulsating compact body moving at constant velocity and showed that amplitude modulation of the source is larger than that predicted by Morse and Ingard [50] because of unsteady drag on the surface of the source. Lighthill [69] and Wright [41] analytically investigated the amplitude modulation of a radiated aerodynamic sound. In addition, Makino and Takano [70–72] investigated the influence of amplitude modulation due to source movement on various high-speed railway noise evaluations by calculating the sound-pressure level of radiated sound from moving discrete monopole point sources in a straight track. Gaunard and Nguyen [73] calculated acoustic power radiated from a source of finite size moving uniformly. Makino and Takano [74] also investigated the influence of sound source movement on the directivities and sound power level of a monopole volume source, a monopole pressure point source, and a dipole pressure point source.

There are several experimental studies about the frequency and amplitude modulations of moving source. For the measurement of frequency modulation, Hoshika *et al.* measured the Doppler effect from an electronic buzzer in a moving train model which is launched in the experimental facility [76]. Akutsu *et al.* [43–47] visualized instantaneous sound fields around a moving sound source using parallel phase-shifting interferometry (PPSI) and the measured Doppler-shifted frequency of the radiated sound agreed well with the theoretical values. For the measurement of amplitude modulation, Norum *et al.* [77] measured the amplitude modulation of shock noise and mixing noise generated from the

jet of a supersonic jet aircraft. However, in the case of high-speed railways such as the Shinkansen, a dipole component of aerodynamic noise caused by pressure fluctuation on a surface, rather than radiated rolling noise from vibration rails and wheels, is dominant at speeds of 300 km/h or higher. Makino *et al.* measured the sound radiated from a moving ultrasonic transducer as a simplified vibrational sound source [78] and an aeolian tone sound radiated from a moving aerodynamic sound source [79, 80].

However, how the source type affects the amplitude modulation of radiated sound due to source movement at low Mach numbers has not yet been clarified experimentally. In other words, no experimental studies have been conducted to validate the accuracy of the analytical solutions of radiated sound pressure field from moving sources introduced in Chapter 2, which are solely analytical formulation based on wave equations.

In this chapter, a lurching experiment was conducted using a moving scaled train model. The train model had an ultrasonic transducer on its surface to simulate a simplified vibrational sound source and an aerodynamic sound source radiating an aeolian tone noise for typical sound of a dipole component of aerodynamic sound. Then the directivities of the two moving sources were measured at different velocities because the amplitudes of radiated sound pressure and, hence, the directivities are modulated because of source movement. On the basis of the experimental results, how the sound source type affects amplitude modulation of radiated sound induced by source movement is discussed at low Mach numbers for these two sources, which are typical for high-speed railway noise. Note that most of this chapter is based on Ref. [81].

3.2 A train model experiment

3.2.1 A scaled train model

Figure 3.1 shows the 1/20-scale train model with an ultrasonic transducer as a vibrational sound source and an aerodynamic sound source. The length, the width and the height of the model is 2,625, 150, and 172.5 mm, respectively.

As a vibrational sound source, an ultrasonic transducer (PT40-17N, Nippon Ceramic) with a radius of 0.005 m was attached to the top of the model and the center of the guide rail. The distance Δx_{VIB} [m] in rail direction between the tip of the nose of the train model and the center of the vibrational sound source is 1,225 mm. The vibrational source radiated a sinusoidal ultrasound ($f_{\text{source}} = 40,290$ Hz, which corresponds to 2,014.5 Hz in a real environment). Under the assumption that the similarity law holds, a sound wave in the audible frequency range behaves the same as an ultrasonic wave.

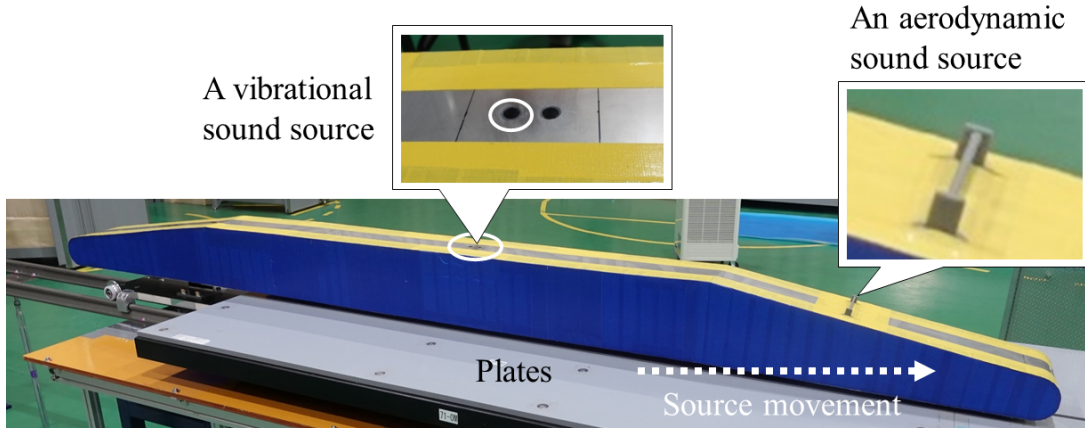


Figure 3.1: A scaled train model with two sound sources.

In this experiment, a cylinder in Fig. 3.2 is used as an aerodynamic sound source. When the source moves in the static air, an aeolian tone is generated from the cylinder with a diameter D of 0.004 m. The distance d from the center of the cylinder to the surface on which the source is attached is 0.011 m. Then the cylinder was attached to the nose of the train model. The distance in the rail direction Δx_{AE} [m] between the tip of the nose of the train model and the center of the cylinder is 378 mm. It is assumed that relative flow velocity at the cylinder is equal to the model velocity V , and that the cylinder generates a Karman vortex at the same frequency of an aeolian tone in free stream. Then

the radiated tone frequency f_{source} [Hz] was obtained as

$$f_{\text{source}} = St \frac{V}{D} \quad (3.1)$$

where St is the Strouhal number, which is determined using the relationship between the Reynolds number Re and St described by Fey *et al.* [82] as

$$St = St_0 + \frac{St_{\text{coef.}}}{\sqrt{Re}} \quad (3.2)$$

where St_0 is 0.1776 and $St_{\text{coef.}}$ is 2.2023 in the interval $5000 < Re < 2 \times 10^5$. The Reynolds number Re can be obtained as

$$Re = \frac{VD}{\nu} \quad (3.3)$$

where ν [m²/s] is the kinematic viscosity determined using U.S. standard atmosphere [83].

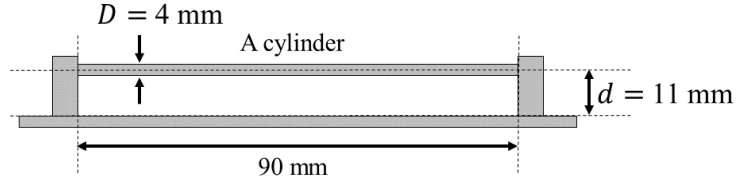


Figure 3.2: An aerodynamic sound source used in a scaled train model experiment.

3.2.2 Low-noise moving model test facility

The experiment was performed using a low-noise moving model test facility at the Railway Technical Research Institute (RTRI) [84]. The total length of the facility is 125 m, comprising three sections: the launch section, the measurement section, and the braking section. The train model was launched in the launch section and then entered the measurement section. The measurement section, where sound radiated from the launched train model was measured, is a semi-anechoic chamber with a length of 40 m. After passing through the measurement section, the train model entered the braking section to decelerate and stop.

Figure 3.3 illustrates the setup of the scaled train model and the semi-anechoic chamber in the low-noise moving model test facility. In this measurement, plates were placed above the guide rails in the measurement section to imitate the ground. The sound radiated from the source was recorded using a 1/4-inch microphone (RION UC-29) and a noise

level meter (RION UN-14), and the sampling frequency was 192 kHz. Figure 3.4 shows the position of the vibrational source, the aerodynamic source, and the microphone. The microphone was located $z_{\text{mic}} (= 360 \text{ mm})$ above the surface of the plates at the center of the guide rails. The surface of the vibrational source was $z_{\text{VIB}} (= 180 \text{ mm})$ above the plate. Hence, the height difference $\Delta z_{\text{VIB}} (= z_{\text{mic}} - z_{\text{VIB}})$ [m] between the source and the microphone was 0.18 m. The center of the aerodynamic sound source was $z_{\text{AE}} (= 143 \text{ mm})$ above the plate and the height difference $\Delta z_{\text{AE}} (= z_{\text{mic}} - z_{\text{AE}})$ [m] between the center of the source and the microphone was 0.217 m. Four infrared sensors in total—two each at the entrance and exit of the semi-anechoic chamber—were used to detect the time when the train model passed each sensor. The distance l between the sensors was 2.0 m at both the entrance and the exit.

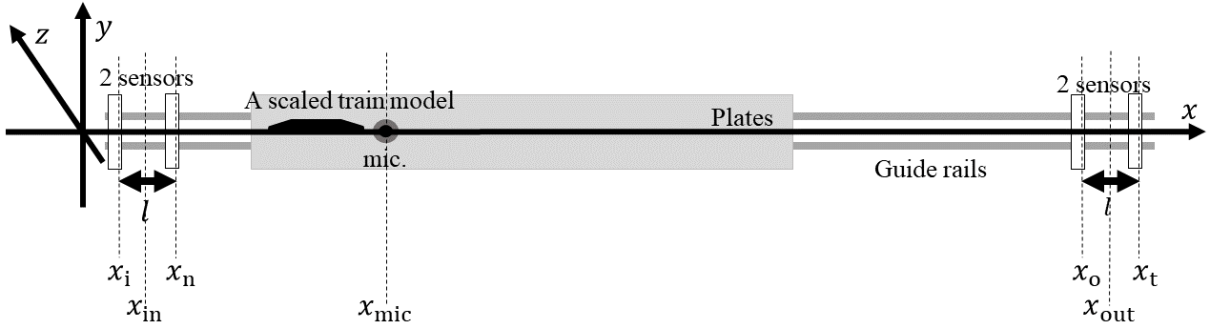


Figure 3.3: Setup of a scaled train model in a semi-anechoic chamber at a low-noise moving model test facility.

3.2.3 Measurement of sound source position and velocity

The x -axis is defined in rail direction and the origin is set as the microphone (Fig. 3.3). Estimated velocity $\mathbf{V}$ and the position of the vibrational sound source $\mathbf{r}_{\text{source,VIB}}$ are defined as

$$\mathbf{V} = \begin{pmatrix} V(t) \\ 0 \\ 0 \end{pmatrix}, \quad (3.4)$$

and

$$\mathbf{r}_{\text{source,VIB}}(t) = \begin{pmatrix} x(t) \\ 0 \\ z_{\text{VIB}} \end{pmatrix}, \quad (3.5)$$

respectively, where $x(t)$ [m] is the position of the vibrational source on the x -axis.

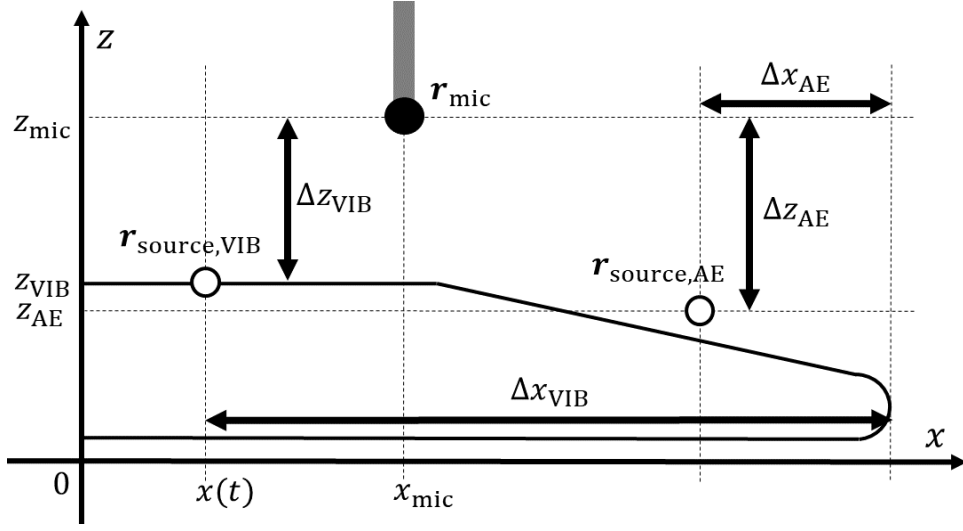


Figure 3.4: Position of a vibrational sound source, an aerodynamic sound source, and 1/4-inch microphone.

Let x_i , x_n , x_o , and x_t [m] be the positions of the sensors on the x -axis from the entrance to the exit of the chamber. In the same manner, let t_i , t_n , t_o , and t_t [s] be the times when the top of the train model passed in front of each sensor. The velocities of the model at the entrance of the chamber V_{in} [m/s] and at the exit of the chamber V_{out} [m/s] can be written as

$$V_{in} = \frac{l}{t_n - t_i} \quad (3.6)$$

and

$$V_{out} = \frac{l}{t_t - t_o}, \quad (3.7)$$

respectively. The positions of the entrance and the exit of the chamber on the x -axis, x_{in} and x_{out} [m], can be written as

$$x_{in} = \frac{x_i + x_n}{2} \quad (3.8)$$

and

$$x_{out} = \frac{x_o + x_t}{2}, \quad (3.9)$$

respectively.

The times t_{in} and t_{out} [s] at which the vibrational source passed x_{in} and x_{out} can be estimated as

$$t_{in} = \frac{t_i + t_n}{2} + \frac{\Delta x_{VIB}}{V_{in}} \quad (3.10)$$

and

$$t_{\text{out}} = \frac{t_o + t_t}{2} + \frac{\Delta x_{\text{VIB}}}{V_{\text{out}}}, \quad (3.11)$$

respectively.

The position of the microphone $\mathbf{r}_{\text{mic}}$ is defined as

$$\mathbf{r}_{\text{mic}} = \begin{pmatrix} x_{\text{mic}} \\ 0 \\ z_{\text{mic}} \end{pmatrix}. \quad (3.12)$$

When the vibrational source radiated sound from directly under the microphone, the sound propagated vertically relative to the source movement; thus, $f = f_{\text{source}}$ because $\cos \theta = 0$ and $D_f = 1$. Thus, the time t_{mic} [s] when the source passed directly under the microphone can be obtained as

$$t_{\text{mic}} = t_{f,\text{source}} - \frac{\Delta z_{\text{VIB}}}{c}, \quad (3.13)$$

where $t_{f,\text{source}}$ [s] is the time when a peak frequency of radiated sound from the source is closest to f_{source} at the microphone. Consequently, the velocity $V(t)$ [m/s] and the position $x(t)$ [m] of the vibrational sound source can be estimated as

$$V(t) = \begin{cases} \frac{x_{\text{in}} - x_{\text{mic}}}{t_{\text{in}} - t_{\text{mic}}} & (t \leq t_{\text{mic}}) \\ \frac{x_{\text{out}} - x_{\text{mic}}}{t_{\text{out}} - t_{\text{mic}}} & (t_{\text{mic}} < t) \end{cases} \quad (3.14)$$

and

$$x(t) = \begin{cases} \frac{x_{\text{in}} - x_{\text{mic}}}{t_{\text{in}} - t_{\text{mic}}}(t - t_{\text{mic}}) + x_{\text{mic}} & (t \leq t_{\text{mic}}) \\ \frac{x_{\text{out}} - x_{\text{mic}}}{t_{\text{out}} - t_{\text{mic}}}(t - t_{\text{mic}}) + x_{\text{mic}} & (t_{\text{mic}} < t) \end{cases}, \quad (3.15)$$

respectively, where x_{mic} [m] is the position of the microphone on the x -axis.

Here, the position of the aerodynamic source $\mathbf{r}_{\text{source,AE}}$ is defined as

$$\mathbf{r}_{\text{source,AE}} = \mathbf{r}_{\text{source,VIB}} + \Delta \mathbf{r}_{\text{source}}, \quad (3.16)$$

where $\Delta \mathbf{r}_{\text{source}}$ is a position vector from the vibrational source to the aerodynamic source and is written as

$$\Delta \mathbf{r}_{\text{source}} = \begin{pmatrix} \Delta x_{\text{VIB}} - \Delta x_{\text{AE}} \\ 0 \\ z_{\text{AE}} - z_{\text{VIB}} \end{pmatrix}. \quad (3.17)$$

3.2.4 Measured directivities of moving sources

Figure 3.5 shows examples of sound spectrogram recorded at the microphone which the vibrational sound source passed directly under the microphone at velocities of (a)197, (b)242, and (c)277 km/h. For the sound radiated from the vibrational sound source, a short time Fourier transform (STFT) was applied to the recorded signal to each 256 samples with 50% overlap and Hanning window. For the sound radiated from the aerodynamic sound source, the STFT was applied to each 1,024 samples with 87.5% overlap and Hanning window.

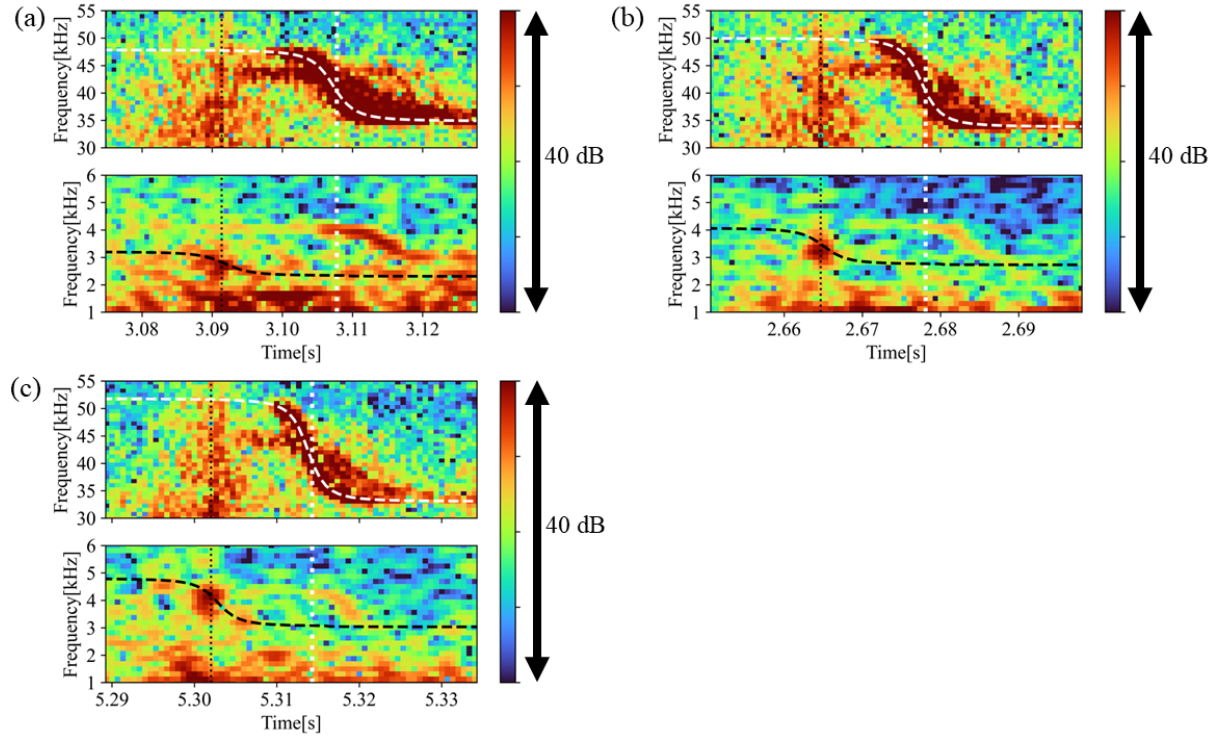


Figure 3.5: Spectrograms of sound recorded by a 1/4-inch microphone, and estimated frequencies of sound radiated from two sources at velocities of (a)197, (b)242, and (c)277 km/h when a vibrational sound source passed directly under the microphone. (White dashed lines: a vibrational sound source; black dashed lines: the cylinder of an aerodynamic sound source). Straight white dotted lines represent the times $t_{f,\text{source}}$ [s] when a peak frequency of radiated sound from the vibrational sound source is closest to f_{source} at the microphone and straight black dotted lines represent the time $t_{\text{peak,AE}}$ [s] when the SPL of the sound radiated from an aerodynamic sound source reaches the peak at the microphone.

The white dashed lines indicate frequencies f [Hz] of sound radiated from the vi-

brational source, as estimated using Eq. (2.3). The results confirm that the estimated and measured frequencies of sound radiated from the vibrational source were in good agreement with each other and that the signal-to-noise ratios of the sound at the microphone were more than 10 dB. The sound pressure level (SPL) $L_{p,\text{mic}}(t)$ [dB] of the radiated sound at the microphone was determined in the range 30–55 kHz, within which the radiated frequency varies because of the Doppler effect.

For the sound radiated from the aerodynamic sound source, $L_{p,\text{mic}}(t)$ [dB] was determined in a range of ± 0.75 kHz from the frequencies f [Hz] estimated according to Eq. (2.3) and Eqs. (3.1)-(3.3). The estimated Re of the aerodynamic source at t_{pass} of the 3 trials in Fig. 3.5 were (a) 1.38×10^4 , (b) 1.73×10^4 , and (c) 1.98×10^4 . The estimation according to Eqs. (3.1)-(3.3) is valid because all the Re is within the range of $5000 < Re < 2 \times 10^5$. On the other hand, Karman vortex generated by the source cylinder may also generate sound source on the train surface in its downstream. However, Nagakura [85] performed wind tunnel tests and a field test using an acoustic mirror, which consists of an omni-directional microphone and a reflector, to reveal that the noise source of the aerodynamic noise from the wiper of Shinkansen trains concentrates at the wiper itself which is attached to the nose of them. Similarly to that, the position of the aerodynamic sound source is set as the position of the source's cylinder in estimating the frequencies f . The black dashed lines and the straight black dotted lines in Fig. 3.5 indicate the estimated frequencies f and the times $t_{\text{peak,AE}}$ [s] when the SPL of the sound radiated from an aerodynamic sound source reaches the peak at the microphone.

Figure 3.6 shows sound spectra of the measured sound at the microphone of these trials at the time $t_{\text{peak,AE}}$. The peak frequency of each spectrum is close to the estimated frequency of the sound radiated from the source (straight dashed lines in the figure) and the peak level of the sound is more than 10 dB from the level of the background noise. Therefore the spectra confirmed that tonal acoustic radiation occurred as well as the cylinder in a freestream due to periodic vortex shedding and that the signal-to-noise ratios of the sound at the microphone were more than 10 dB within the range.

In addition, the straight white dotted lines in Fig. 3.5 represent the times $t_{f,\text{source}}$. The distance l_{peaks} [m] which the train model moved from $t_{\text{peak,AE}}$ to $t_{f,\text{source}}$ is written as

$$l_{\text{peaks}} = x(t_{f,\text{source}}) - x(t_{\text{peak,AE}}), \quad (3.18)$$

which of the 3 trials in Fig. 3.5 are (a)905, (b)908, and (c)950 mm. They are longer than the distance in rail direction between the vibrational source and the aerodynamic

source $\Delta x_{\text{VIB}} - \Delta x_{\text{AE}} (= 847 \text{ mm})$ at all the trials. Therefore the figures can confirm that aerodynamic sound is not radiated from the wake from the cylinder but from the surface of the cylinder in this experiment. As well as that, the figures suggest that the radiation angle can be leaning in the direction of source movement from the vertical where the SPL of radiated sound takes the maximum value.

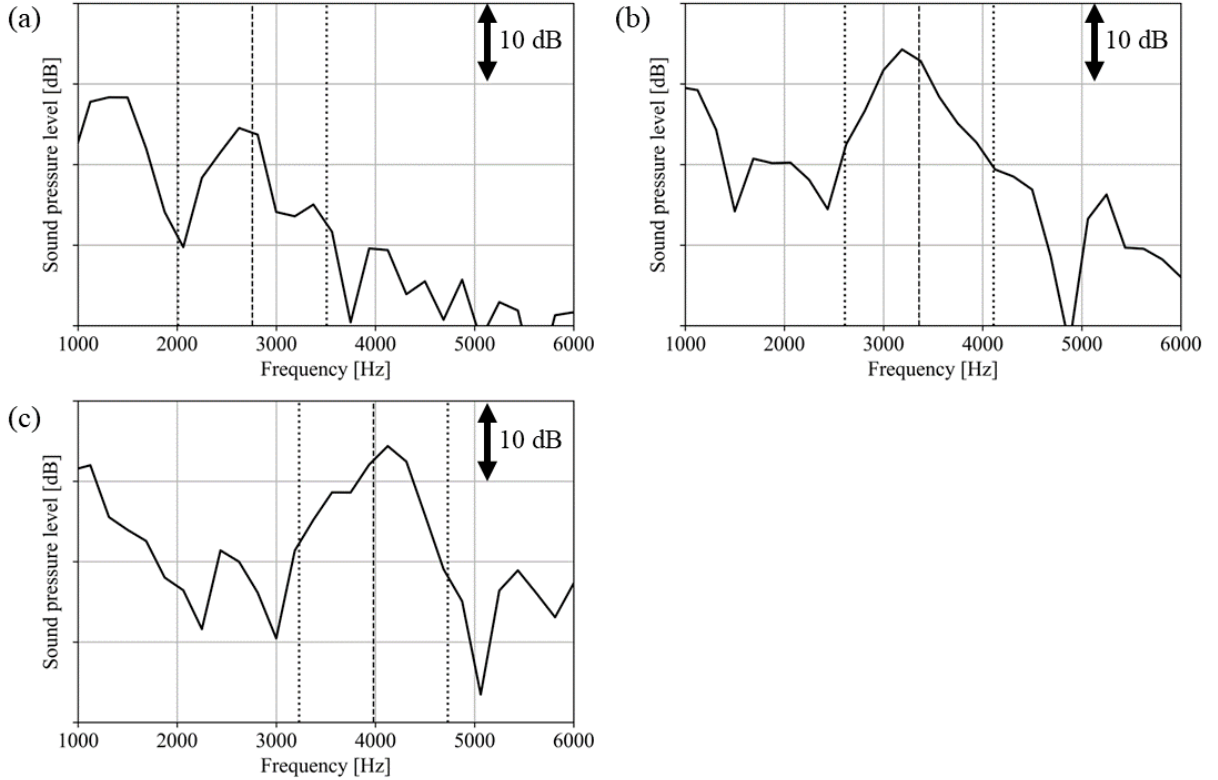


Figure 3.6: Spectra of sound recorded by a 1/4-inch microphone at the time when the SPL of the sound radiated from an aerodynamic sound source reaches the peak. The velocities of the scaled train model are (a)197, (b)242, and (c)277 km/h when a vibrational sound source passed directly under the microphone. (Straight dashed lines: the estimated frequencies of the aeolian tone from the cylinder of an aerodynamic sound source at the time; straight dotted lines: the frequencies $\pm 0.75 \text{ kHz}$.)

The SPL $L_{\text{dir}}(\theta)$ [dB] of the radiated sound at a unit distance in the direction θ from the source can be written using $R = |\mathbf{R}(t)|$ [m] as

$$L_{\text{dir}}(\theta) = L_{p,\text{mic}} \left(t + \frac{R}{c} \right) + 20 \lg R + \alpha(f) R, \quad (3.19)$$

by correcting a distance attenuation. In the present work, $L_{\text{dir}}(\theta)$ [dB] is defined as the directivity of sound radiated from a moving sound source. The last term in Eq. (3.19)

represents air absorption, where $\alpha(f)$ [dB/m] is the air absorption coefficient calculated according to ISO 9613-1:1993 [86]. Because $\alpha(f)$ is less than 1 dB/m at the frequencies less than 10 kHz, the term can be neglected for aerodynamic sound in the experiment.

3.2.5 Results

For the vibrational sound source, the directivities of radiated sound were measured in 12 trials in which the vibrational source passed directly under the microphone at different velocities between 100 and 300 km/h. Figure 3.7 shows the measured directivities L_{dir} of sound radiated from the vibrational source.

For the aerodynamic sound source, the directivities of radiated sound were measured in 3 trials in which the source passed directly under the microphone at velocities of (a)197, (b)242, and (c)277 km/h. Figure 3.8 shows the measured directivities L_{dir} [dB]. The measured SPL was sufficiently high compared with background noise in the radiation angle θ range: (a)from 25° to 115°, (b)from 30° to 135°, and (c)from 30° to 120°. Thus, the amplitude modulation of the radiated sound was derived using the measured directivities within this range.

3.3 Discussion

The directivity of a moving source consists of two components:

$$L_{\text{dir}}(\theta) \equiv L_{\text{dir}}\left(\frac{\pi}{2}\right) + \Delta L_{\text{source}} + \Delta L_{\text{Doppler}}. \quad (3.20)$$

Here, ΔL_{source} [dB] is a source term that depends on the directivity characteristics of the sound source and $\Delta L_{\text{Doppler}}$ [dB] is a motion term that depends on the source's movement [87].

In this section, the motion terms $\Delta L_{\text{Doppler}}$ of the vibrational sound source and the aerodynamic sound source are determined by estimating the source terms ΔL_{source} of the measured directivities. How the type of sound source affects the amplitude modulation of radiated sound induced by source movement for these sources is then discussed.

3.3.1 Source term

The vibrational sound source is regarded as a circular panel vibrating uniformly in an infinite baffle. Sound pressure $p(|\mathbf{R}|, \theta)$ [Pa] radiated from the stationary panel at the

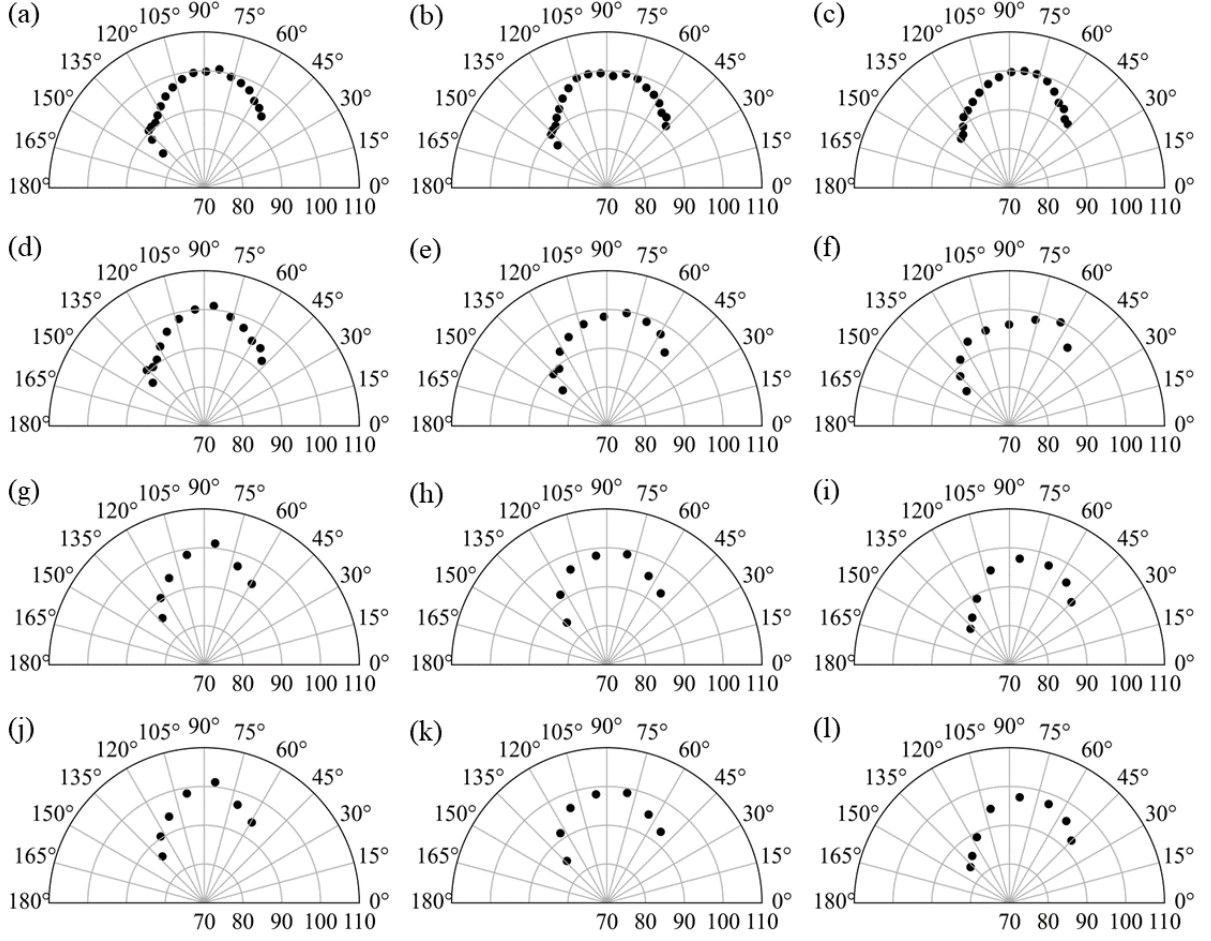


Figure 3.7: Measured directivities $L_{\text{dir}}(\theta)$ [dB] of a vibrational sound source on a scaled train model moving at different velocities: (a) 108 km/h, (b) 109 km/h, (c) 109 km/h, (d) 155 km/h, (e) 197 km/h, (f) 240 km/h, (g) 241 km/h, (h) 241 km/h, (i) 241 km/h, (j) 242 km/h, (k) 277 km/h, and (l) 289 km/h.

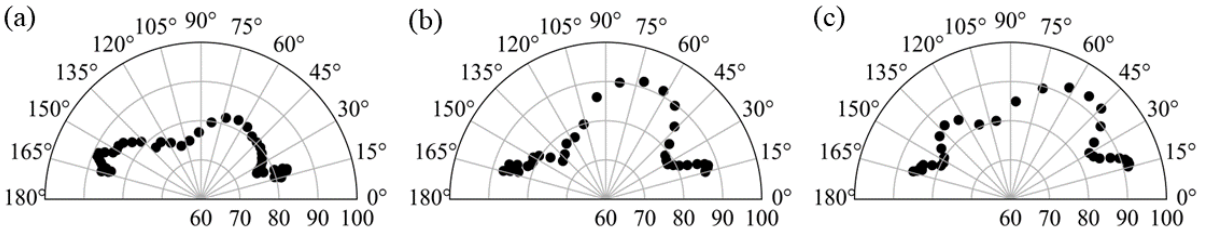


Figure 3.8: Measured directivities $L_{\text{dir}}(\theta)$ [dB] of an aerodynamic sound source measured in a scaled train model experiment: (a) 197 km/h, (b) 242 km/h, and (c) 277 km/h.

observer can be represented as [88]

$$p(|\mathbf{R}|, \theta) = 2p\left(|\mathbf{R}|, \frac{\pi}{2}\right) \frac{J_1(kr_{\text{panel}}|\cos\theta|)}{kr_{\text{panel}}|\cos\theta|} \quad (3.21)$$

where $k(= 2\pi f_{\text{source}}/c)$ [rad/m] is the wave number of radiated sound, r_{panel} [m] is the radius of the panel, and J_1 is the first-order Bessel function of the first kind. Thus, ΔL_{source} can be represented as

$$\Delta L_{\text{source}} = 20 \lg \left[2 \frac{J_1(kr_{\text{source,eq}}|\cos\theta|)}{kr_{\text{source,eq}}|\cos\theta|} \right] \quad (3.22)$$

where $r_{\text{source,eq}}$ [m] is an equivalent radius of the surface of the vibrational source. Thus $\Delta L_{\text{Doppler}}$ was obtained by using Eq. (3.20) and then by computing a linear regression line for $10 \lg D_f$ [dB] and $\Delta L_{\text{Doppler}}$. Subsequently, $r_{\text{source,eq}}$ [m] was determined as the radius that leads to the smallest standard deviation of the regression and sufficient separation of amplitude modulations because of the source itself and source movement.

On the other hand, the directivity of the aerodynamic sound source is modeled as a dipole. To consider sound reflection at the surface of the train model, it is assumed that the surface which the source is attached is infinite panel, and an image source of the aerodynamic source is also assumed. Figure 3.9 shows the geometry of the aerodynamic sound source $\mathbf{r}_{\text{source}}$, an image source of that $\mathbf{r}'_{\text{source}}$, and the microphone $\mathbf{r}_{\text{mic}}$. The combined sound pressure $p(\theta)$ [Pa] from the source and the image source at the microphone can be expressed as

$$p(\theta) = \frac{\exp(ik|\mathbf{R}|)}{4\pi|\mathbf{R}|} \cos(\theta_{\text{peak}} - \theta) - \frac{\exp(ik|\mathbf{R}'|)}{4\pi|\mathbf{R}'|} \cos(\varepsilon - \gamma) \quad (3.23)$$

where $\mathbf{R}'$ is a vector from the image source to the microphone. The terms $|\mathbf{R}|$ and $|\mathbf{R}'|$ can be respectively derived as

$$|\mathbf{R}| = \frac{\Delta z_{\text{AE}}}{\sin\theta} \quad (3.24)$$

and

$$|\mathbf{R}'| = \sqrt{\left(\frac{\Delta z_{\text{AE}}}{\tan\theta} + 2d \sin\beta\right)^2 + (\Delta z_{\text{AE}} + 2d \cos\beta)^2}, \quad (3.25)$$

where $\beta(= 0.165 \text{ rad})$ is the slope of the nose of the train model and approximately 8.9° . Here, $d(= 0.011 \text{ m})$ is the distance from the center of the cylinder of the source to the surface on which the source is attached and ε [rad] is the angle between the direction from the image source to the real source and to the microphone, written as

$$\varepsilon = \arcsin \left[\frac{|\mathbf{R}|}{|\mathbf{R}'|} \cos(\theta + \beta) \right]. \quad (3.26)$$

In addition, γ [rad] is the angle between the direction in which the SPL of radiated sound takes the maximum value and the direction perpendicular to the plate to which the aerodynamic source is attached, written as

$$\gamma = \theta_{\text{peak}} - \left(\frac{\pi}{2} - \beta \right), \quad (3.27)$$

where θ_{peak} [rad] is the angle between source movement and the direction in which the SPL of radiated sound takes the maximum value. ΔL_{source} can be written as

$$\Delta L_{\text{source}} = 20 \lg \left| \frac{p(\theta)}{p(\pi/2)} \right| + 20 \lg \left(\frac{|\mathbf{R}|}{\Delta z_{\text{AE}}} \right) \quad (3.28)$$

by correcting a distance attenuation in the last term.

However, θ_{peak} can differ by trial because flow direction at the position of the cylinder of the source can differ by Mach number or Reynolds number due to the effects of the train model surface on the mean flow and turbulence around the cylinder. Therefore θ_{peak} or ΔL_{source} were determined on each trial as the angle that results in the smallest standard deviation of a linear regression line for $10 \lg D_f$ [dB] and $\Delta L_{\text{Doppler}}$ [dB] on the measured data.

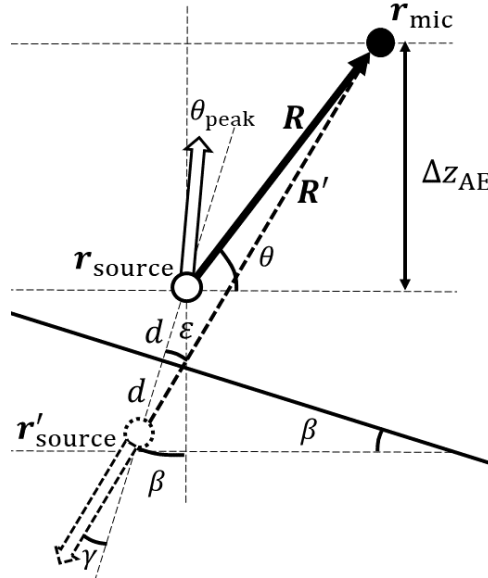


Figure 3.9: Geometry of an aerodynamic sound source $\mathbf{r}_{\text{source}}$, an image aerodynamic sound source $\mathbf{r}'_{\text{source}}$, and a microphone $\mathbf{r}_{\text{mic}}$.

3.3.2 Doppler factor and amplitude modulation due to source movement

Figure 3.10 demonstrates measured amplitude modulations $\Delta L_{\text{Doppler}}$ [dB] of sound radiated from the vibrational source because of source movement. The straight broken line indicates their linear regression. The slope of the line is 4.34, and the standard deviation of the regression is 1.08 dB. The value of the slope represents the exponent of acoustic intensity to D_f . The results suggest that the acoustic intensity is proportional to approximately the fourth power of the Doppler factor.

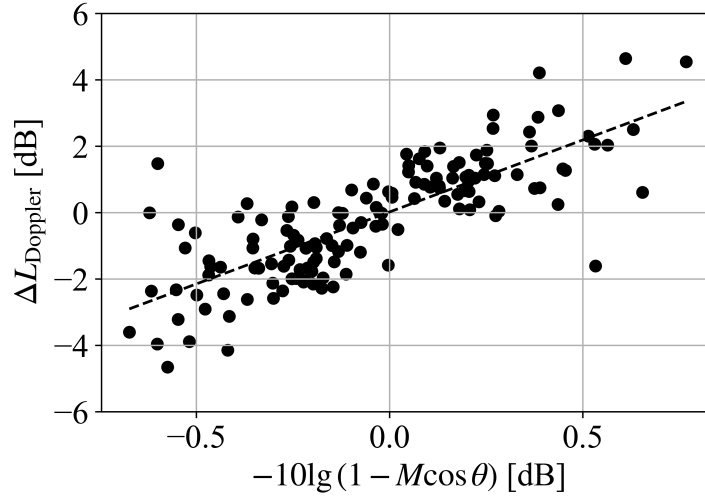


Figure 3.10: Amplitude modulations due to source movement $\Delta L_{\text{Doppler}}$ [dB] of a vibrational sound source, as measured in a scaled train model experiment. (Straight broken line: linear regression of plotted data.)

According to Eq. (2.13), sound pressure from a monopole point source (pulsating sphere) moving at a constant velocity is approximately proportional to the second power of the Doppler factor. By contrast, Dowling [68] showed that sound pressure from a pulsating body moving at constant velocity is more amplified than the one proportional to the third power of the Doppler factor because of unsteady drag on the pulsating surface. However, the surface of the vibrational sound source is parallel to the source movement direction in the present experiment. Thus, it is speculated that there is no drag but lift on the source, thereby showing good agreement between the measured amplitude modulation of the vibrational source and the results of the analytical study of Morse and Ingard [50].

Figure 3.11 shows the measured amplitude modulations $\Delta L_{\text{Doppler}}$ [dB] of the aerody-

namic source; the straight broken line in the figure represents their linear regression. The slope of the line is 8.77, and the standard deviation of the regression is 2.46 dB. The results show that the sound pressure and the acoustic intensity is respectively proportional to approximately the fourth power and the eighth power of the Doppler factor because half the value of the slope represents the exponent of radiated sound pressure to D_f and is 4.39. The estimated θ_{peak} value is (a)69.5°, (b)79.7°, and (c)79.4°. The figure also shows that the plotted data are widely scattered within the range $0.6 < -10 \lg(1 - M \cos \theta)$ because, for example, the wavelength of the radiated sound is longer than that of the vibration source, which results in a large error in the measured $\Delta L_{\text{Doppler}}$ because of the assumption that the surface to which the source is attached is an infinite plate.

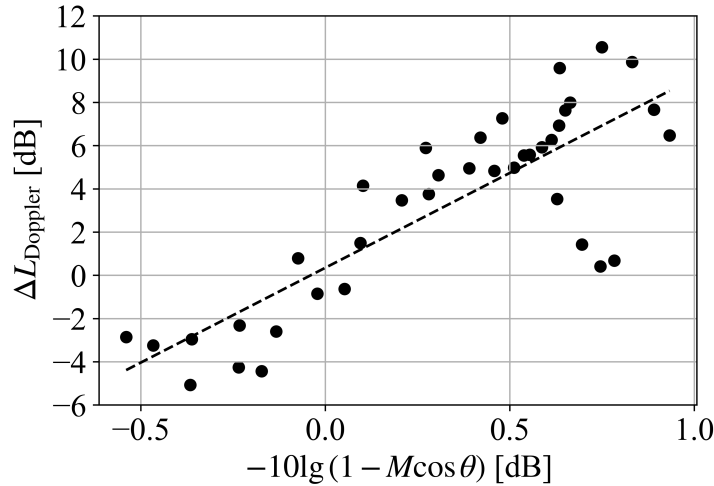


Figure 3.11: Amplitude modulations due to source movement $\Delta L_{\text{Doppler}} [\text{dB}]$ of an aerodynamic sound source, as measured in a scaled train model experiment. (Straight broken line: linear regression of plotted data.)

Wright [41] conducted a theoretical study on aerodynamic sound radiated in the far field from a moving sound source, which was sufficiently small relative to the wavelength, and Wright found that the sound pressure of aerodynamic sound observed at a stationary observer is proportional to the $3 + P$ th power of D_f , where P is the order of the multipole ($P = 0, 1$, or 2 for a monopole, dipole, or quadrupole sound source, respectively). The sound source of an aeolian tone sound has a dipole directivity (i.e., $P = 1$). Thus, the sound pressure and the acoustic intensity are proportional to the fourth and eighth powers of D_f , respectively. Consequently, the amplitude modulation measured in the scaled train

model experiment shows good agreement with that predicted in the theoretical study of Wright [41].

Comparing the exponents of acoustic intensity to D_f obtained from the measured directivities reveals that the exponent of the aerodynamic sound source is larger than that of the vibrational sound source. Therefore, it is confirmed experimentally that the exponent of the sound pressure depends on the physical mechanism of the source. Compared with the sound radiated from a vibrational sound source, that radiated from an aerodynamic sound source is more amplified by source movement when the source passes in front of a receiver at a speed in the low Mach number range.

3.4 Summary

A launching experiment was performed using a scaled train model with an ultrasonic transducer as a simplified vibrational sound source and with an aerodynamic sound source radiating aeolian tone sound, which is a typical dipole component of aerodynamic sound. The measurements of directivities of these moving sources were conducted at various source velocities at low Mach numbers to derive motional amplitude modulations of radiated sound. Then how the two sound source types affect the amplitude modulation of radiated sound is investigated as a result of source movement. The experimental results revealed that the acoustic intensity of sound radiated from the vibrational sound source increases roughly in proportion to the fourth power of the Doppler factor, whereas that of the dipole component of aerodynamic sound increases roughly in proportion to the eighth power of the Doppler factor. These results confirmed that the exponent of the sound pressure depends on the physical mechanism of the source. Then they suggest that sound radiated from an aerodynamic sound source leads to a larger amplitude modulation than that radiated from a vibrational sound source at a low Mach number, indicating the necessity of applying corrections for the sound source movement for each physical mechanism of sound source in noise prediction models.

Chapter 4

Source movement and convection of aeolian tone sound

4.1 Introduction

In the previous chapter, amplitude modulation caused by sound source movement was experimentally investigated through the launching experiment. Aerodynamic sound was measured from moving aerodynamic sources in the atmosphere at rest (or where the speed of wind can be neglected) using stationary microphones, which is the same way as a field test. Once the sound has been radiated by the sources, it propagates through the atmosphere at rest and reaches the microphones. The Doppler effect then occurs in the sound field, and the wavelength of the sound changes.

On the other hand, wind tunnel experiments have been conducted to measure the sound instead of a field test or a launching experiment. Beamforming in the experiments has also experienced major developments and has been validated in terms of functionality and accuracy of results [89] as well as pass-by tests. As mentioned in Section 2.4, although the frequency modulation (Doppler effect) does not occur because the sources and microphones are stationary, the source appears to move in the opposite direction to the air flow from the viewpoint of an observer moving with the flow. Therefore, the spatial expansion or contraction of the apparent wavelength of the radiated sound due to the Mach number of the sound source or the air flow is a phenomenon common to both source movement and convection.

Lighthill [69], Dowling [68], and Wright [41] theoretically investigated the amplitude modulation of radiated sound as a result of sound source movement. Morse and Ingard [50] described analytical solutions for radiated sound from a moving monopole point source.

Howe [51] also described analytical solutions for radiated sound from a moving point monopole, dipole, and quadrupole of an aerodynamic source. Makino and Takano [74] investigated the influence of sound source movement on directivities and sound power level of a single volume monopole, volume dipole and pressure point source.

For experimental investigation, Tanigawa *et al.* [90] visualized the sound pressure field of aerodynamic sound in near-field around a square cylinder and fat plates using PPSI, which can avoid becoming new aerodynamic noise sources inside the air flow and affecting the flow itself. Akutsu *et al.* [48] visualized sound wave affected by airflow distribution around the scaled train model in a wind tunnel using PPSI as well as the launching experiment. They observed the changes of the sound wave propagation characteristics such as wavefront distortion, sound trapped in the boundary layer, shadow zone formation, and sound wavelength modulation in the airflow. Makino *et al.* [81] conducted an experiment using a moving scaled train model to measure the directivities of moving sources at different velocities. The results in the experiment suggest that the radiation of sound from an aerodynamic sound source leads to a larger amplitude modulation than the radiation of sound from a vibrational sound source when the sound waves pass in front of a receiver at low Mach number. Then they also measured sound radiated from a moving aerodynamic sound source and an aeolian tone sound radiated from a sound source fixed in a wind tunnel [79, 80].

Amplitude modulations of the radiated sound due to both source movement and convection influence the measured directivity of the radiated sound or the transportation noise prediction based on the directivity. However, how source movement or convection affects the amplitude modulation of radiated aerodynamic sound at low Mach number has not been clarified experimentally.

In this chapter, a wind-tunnel experiment was conducted to emulate the movement of a sound source in air without flow to compare the amplitude modulation caused by source movement with that caused by convection. The source radiates aeolian tone noise for typical sound of a dipole component of aerodynamic sound. The directivities of the source fixed in the wind tunnel were measured using horizontally aligned microphones outside the flow, and the amplitude modulations of the radiated sound by convection were derived. Finally, the influence of source movement on amplitude modulation of the radiated sound is discussed, especially compared with the influence of convection. This chapter is mostly based on Ref. [91].

4.2 Wind tunnel experiment

The directivity of sound radiated in a wind tunnel was measured for an aerodynamic source fixed in air flow. The same aerodynamic sound source as the source in the scaled train model experiment (Fig. 3.2) is used in this experiment. Assuming that the cylinder generates a Karman vortex at the same frequency as a free-stream aeolian tone, the radiated tone frequency f_{source} [Hz] and Re can be derived as

$$f_{\text{source}} = St \frac{V_{\text{flow}}}{D}, \quad (4.1)$$

and

$$Re = \frac{V_{\text{flow}} D}{\nu} \quad (4.2)$$

as well as the scaled train model experiment in the previous chapter.

4.2.1 Wind tunnel

Figure 4.1 shows the wind tunnel used in the experiment. A ground plate was installed at the same height as the bottom of the wind tunnel nozzle. The aerodynamic sound source was fixed on the plate at the center of the outlet cross section so that the cylinder of the source is perpendicular to the flow.

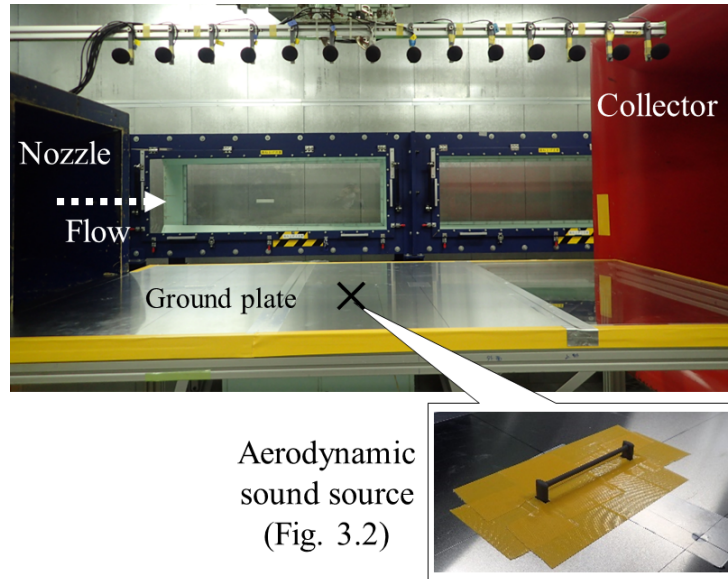


Figure 4.1: A sound source in a wind tunnel and 14 microphones aligned horizontally.

Figure 4.2 illustrates the positions of the cylinder and the microphones, and the region of the flow and the shear layer in the wind tunnel. The distance in the flow direction between the edge of the nozzle and the source x_{AE} [m] is (a) 0.2 m, (b) 0.7 m, and (c) 1.2 m. Fourteen microphones (GRAS 40PH) were aligned at a height z_{mic} of 0.55 m from the ground plate and at the center of the outlet cross section. The microphones were placed at equal intervals of 0.1 m. The distance x_{mic} [m] between the nozzle and each microphone was 0.1 m for the closest microphone to the nozzle and 1.4 m for the farthest one.

The sound radiated from the source was recorded using a wide band data recorder (TEAC WX-7000), and the sampling frequency was 96 kHz. A Fourier transform was applied to the recorded signals of each microphone, which were composed of 16,384 samples; the Fourier transform was applied with 50% overlap and the Hanning window.

In addition, a thermometer was installed on the surface of the collector to measure the air temperature in the wind tunnel for each measurement. The sound speed and the kinematic viscosity in the wind tunnel were estimated using the measured temperature.

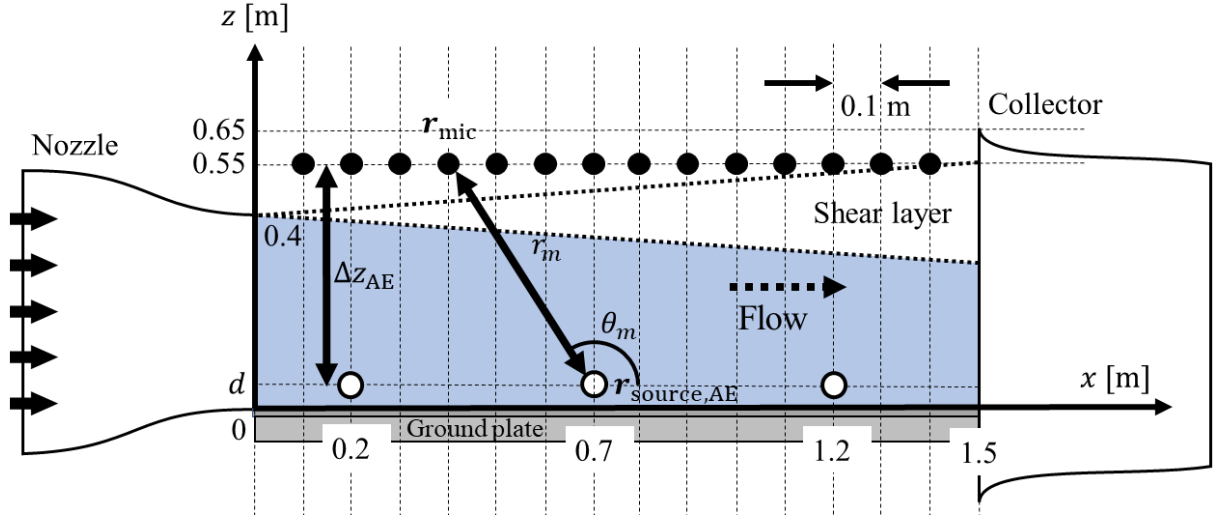


Figure 4.2: Positions of a cylinder of an aerodynamic sound source and 14 microphones, and the region of the flow and the shear layer in the wind tunnel.

4.2.2 Flow velocities at the source position

The aerodynamic sounds were recorded at three different flow velocity settings in the wind tunnel: (i) 54.2 m/s (195 km/h), (ii) 66.7 m/s (240 km/h), and (iii) 77.8 m/s (280 km/h) at the edge of the nozzle in the flow direction and the center of the cross-section

of the nozzle. The Mach numbers of the flow velocity settings are (i)0.159, (ii)0.196, and (iii)0.229 where the sound speed c is 340 m/s.

However, actual flow velocities V_{flow} at the source position were estimated from the measured frequencies of the aeolian tone f_{source} . At first, the frequencies f_{source} were obtained as the dominant frequencies in the spectrum of the measured aeolian tone. Substituting Eqs. (4.1)(4.2) into Eq. (3.2), Eq. (3.2) can be written as

$$\frac{f_{\text{source}}D}{V_{\text{flow}}} = St_0 + \frac{St_{\text{coef.}}}{\sqrt{\frac{V_{\text{flow}}D}{\nu}}} \quad (4.3)$$

and actual flow velocity can be derived as

$$V_{\text{flow}} = \left(\frac{-St_{\text{coef.}}\sqrt{\frac{\nu}{D}} + \sqrt{St_{\text{coef.}}^2\frac{\nu}{D} + 4St_0f_{\text{source}}D}}{2St_0} \right)^2 \quad (4.4)$$

because $0 \leq V_{\text{flow}}$.

Figure 4.3 shows sound spectra of the aerodynamic source ((b) $x_{\text{AE}} = 0.7$ m) measured at the microphone at $x_{\text{mic}} = 0.7$ m with different flow velocity settings of (i)54.2 m/s (195 km/h), (ii)66.7 m/s (240 km/h), and (iii)77.8 m/s (280 km/h). Solid lines and dotted lines represent the sound spectrum measured at the microphone with and without the sound source. The spectra confirmed that tonal acoustic radiation occurred as well as the cylinder effect in a freestream because of periodic vortex shedding and that the signal-to-noise ratios of the sound at the microphone were more than 10 dB because the peak levels of the sound with the source at the peak frequencies were more than 10 dB from the levels of the sound without the source.

Table 4.1 shows the estimated flow velocities V_{flow} and Reynolds numbers Re in the experiment. The table confirmed that the estimate using Eq. (4.4) is valid because Re at all the case is within the range of $5000 < Re < 2.0 \times 10^5$.

4.2.3 SPL of an aeolian tone

The SPL $L_{p,\text{mic}}$ [dB] of the aerodynamic sound radiated from the source was obtained as the difference of the acoustic energy of the measured sound with or without the source. At first, the SPL at the each microphone $L_{p,w}$ [dB] was measured when the wind tunnel works and the source was fixed in the flow. Then the SPL at the each microphone

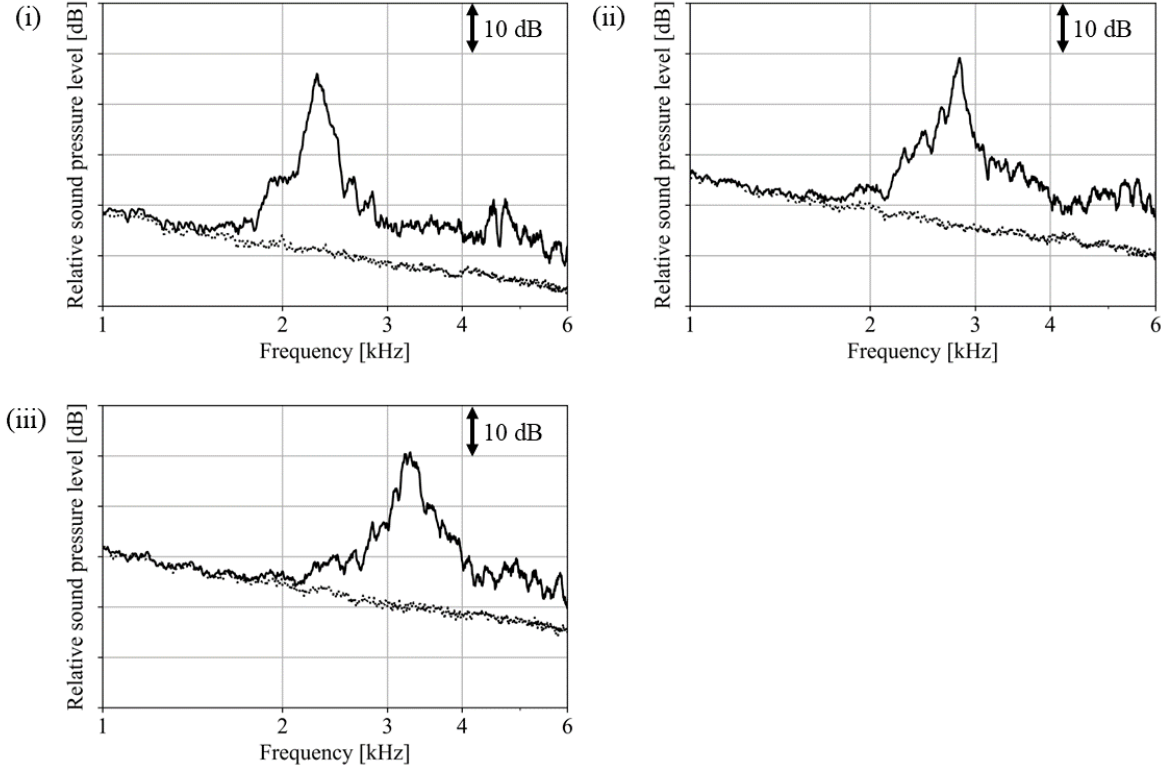


Figure 4.3: Measured sound spectra of the aeolian tone from the aerodynamic source ((b) $x_{\text{AE}} = 0.7$ m) at the microphone located at $x_{\text{mic}} = 0.7$ m, where the flow velocity setting was (i) 54.2 m/s (195 km/h), (ii) 66.7 m/s (240 km/h), and (iii) 77.8 m/s (280 km/h). (Solid lines and dotted lines represent the sound spectrum measured at the microphone with and without the sound source.)

Table 4.1: Estimated flow velocities V_{flow} [m/s], Mach numbers of air flow M_{flow} , and Reynolds numbers Re at the sound source position.

Flow velocity setting	x_{AE} [m]	V_{flow} [m/s]	M_{flow}	Re
(i) 54.2 m/s (195 km/h)	(a) 0.2	50.2	0.145	1.31×10^4
	(b) 0.7	46.3	0.134	1.19×10^4
	(c) 1.2	43.9	0.127	1.18×10^4
(ii) 66.7 m/s (240 km/h)	(a) 0.2	61.6	0.178	1.59×10^4
	(b) 0.7	57.5	0.166	1.45×10^4
	(c) 1.2	54.4	0.157	1.35×10^4
(iii) 77.8 m/s (280 km/h)	(a) 0.2	71.9	0.208	1.83×10^4
	(b) 0.7	66.9	0.193	1.72×10^4
	(c) 1.2	63.0	0.181	1.63×10^4

$L_{p,w/o}$ [dB] was also measured when the wind tunnel works but the source was removed in the flow. $L_{p,mic}$ [dB] at the each microphone is obtained as

$$L_{p,mic} = 10 \lg \left(10^{\frac{L_{p,w}}{10}} - 10^{\frac{L_{p,w/o}}{10}} \right) \quad (4.5)$$

in the frequency range in which the level difference of the measured sound spectra with and without the source was within -10 dB of the difference at the peak frequency f_{source} .

4.2.4 Correcting the refraction of a shear layer

A shear layer is formed at the boundary between flow and stationary air. When a radiated sound propagates from inside the flow to the outside, the sound wave is refracted on the shear layer [92]. The influence of the refraction on sound pressures measured at each microphone was corrected to determine the measured directivities of the cylinder. The corrected sound pressure refers to the pressure when there is the same flow as at the source position at the extent of the height of the microphone.

Figure 4.4 shows a schematic of the refraction of propagating sound by a shear layer. Here, r_m [m] and θ_m [rad] are the distance from the source to the microphone (propagation path) and the angle between the direction in which the radiated sound propagates and the flow (propagation angle) when no flow is present, respectively:

$$r_m = \sqrt{(x_{mic} - x_{AE})^2 + \Delta z_{AE}^2}, \quad (4.6)$$

and

$$\theta_m = \arccos \left(\frac{x_{mic} - x_{AE}}{r_m} \right), \quad (4.7)$$

where $\Delta z_{AE}(= z_{mic} - d)$ [m] is the distance from the source to the microphone in the height direction. Parameters θ_c and θ' [rad] are the angles before and after the refraction. The corrected position of the microphone $\mathbf{r}_{mic,c}$ indicates the position where the sound radiated from the source reaches at the height of the microphones if there is no shear layer or refraction.

From the viewpoint of an observer moving with the air flow, the radiated sound can be regarded as the sound emitted at a retarded position of the cylinder $\mathbf{r}_{source,r}$ and that propagates in the direction from $\mathbf{r}_{source,r}$ to $\mathbf{r}_{mic,c}$. Parameter θ_r [rad] is the angle between the direction from $\mathbf{r}_{source,r}$ to $\mathbf{r}_{mic,c}$ and the flow. These angles have relationships as

$$\frac{\cos \theta_r + M_{flow}}{\sin \theta_r} = \frac{1}{\tan \theta_c} \quad (4.8)$$

and

$$\frac{1}{\cos \theta_r} + M_{\text{flow}} = \frac{1}{\cos \theta'}. \quad (4.9)$$

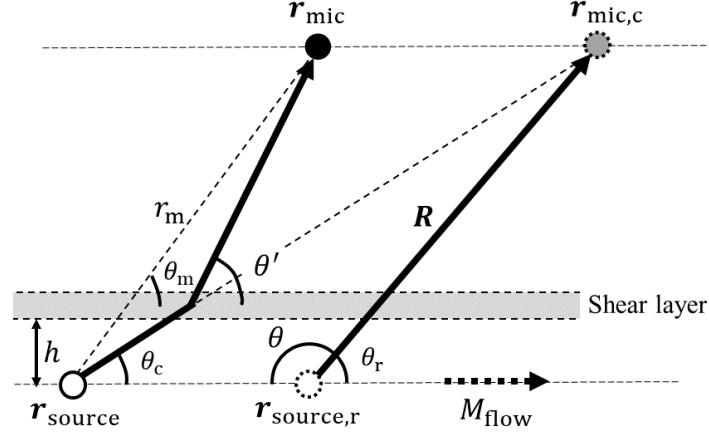


Figure 4.4: Correction of refraction by a shear layer.

Assuming that the shear layer is planar and that the thickness of the shear layer is sufficiently small compared with the wavelength of the radiated sound, the corrected sound pressure p_{c0p} [Pa] is obtained as (see Eq. (A.7))

$$\begin{aligned} \left| \frac{p_{c0p}}{p_{\text{mic}}} \right| &= \frac{(1 + M_{\text{flow}} \cos \theta_r)^2 + \mu}{2(1 + M_{\text{flow}} \cos \theta_r)^2 \mu^2} \\ &\times \frac{\sin \theta_m}{\sin \theta_r} \sqrt{[1 + \sigma(\mu - 1)][1 + \sigma(\mu^3 - 1)]}, \end{aligned} \quad (4.10)$$

where

$$\mu = \frac{\sqrt{(1 + M_{\text{flow}} \cos \theta_r)^2 - \cos^2 \theta_r}}{\sin \theta_r}; \quad (4.11)$$

$$\sigma = \frac{h}{r_m \sin \theta_m}; \quad (4.12)$$

p_{mic} [Pa] is the measured pressure at the microphone; h [m] is the distance from the cylinder to the boundary between the potential core and the shear layer in height direction.

Figure 4.5 shows the normalized flow velocities (the ratios of the measured flow velocity to the flow velocity setting) in the wind tunnel at flow velocity setting of (iii) 77.8 m/s (280 km/h) using a Pitot tube. The $\times$ marks represent the positions which the flow velocity is so slow that it is supposed to be outside the flow. The $\star$ marks represent the positions where it is estimated to be inside the potential core because the velocity is as

fast as the flow velocity setting. Then the area between the two dashed lines represents the estimated shear layer assuming that the boundaries between the shear layer and both the potential core and the stationary air are planar. It is estimated that h can be in the range of approximately $0.25 < h \leq 0.4$ at the maximum flow velocity setting based on the figure. In this study, the corrected sound pressures were determined where $h = 0.35$ m for all the measured data because the pressures are within ± 1 dB from the level when h is set as 0.35 m in calculation (see Fig. A.1).

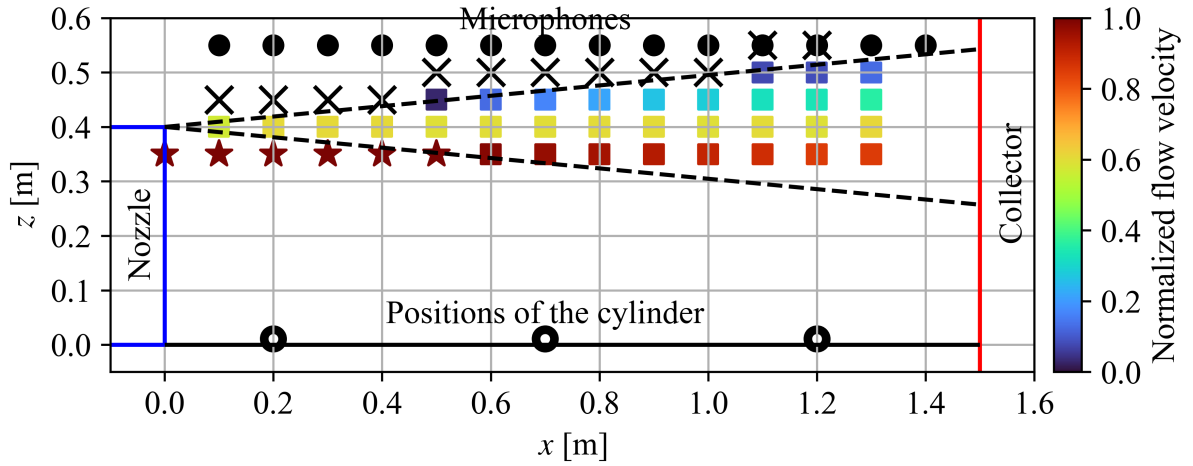


Figure 4.5: Normalized flow velocities (the ratios of the measured flow velocity to the flow velocity setting) of (iii) 77.8 m/s (280 km/h). The $\times$ marks represent the positions which the flow velocity is so slow that it is supposed to be outside the flow. The area between the two dashed lines represents the estimated shear layer.

4.2.5 Results

From the viewpoint of an observer moving with the air flow, the radiation angle of the radiated sound shown in Fig. 2.5 is $\theta = \pi - \theta_r$ [rad] and the directivity of the radiated sound L_{dir} [dB] is defined as the SPL of the source propagated in the air at a unit distance, calculated as

$$L_{\text{dir}}(\theta) \equiv L_{p,\text{mic}} + 20 \lg \left| \frac{p_{c0p}}{p_{\text{mic}}} \right| + 20 \lg |\mathbf{R}|, \quad (4.13)$$

where $L_{p,\text{mic}}$ [dB] is the SPL of the source at the microphone and $|\mathbf{R}|$ [m] is the propagation distance of the sound which is obtained as

$$|\mathbf{R}| = \frac{\Delta z_{\text{AE}}}{\sin \theta}. \quad (4.14)$$

Figure 4.6 illustrates the measured directivities of sound radiated from the source fixed in the wind tunnel at three different positions with three different flow velocity settings. Measured data plotted with $\times$ marks were excluded from a following analysis of amplitude modulations because the sound reflection from the nozzle and collector in the wind tunnel and resulting sound wave interference degraded the measured data significantly.

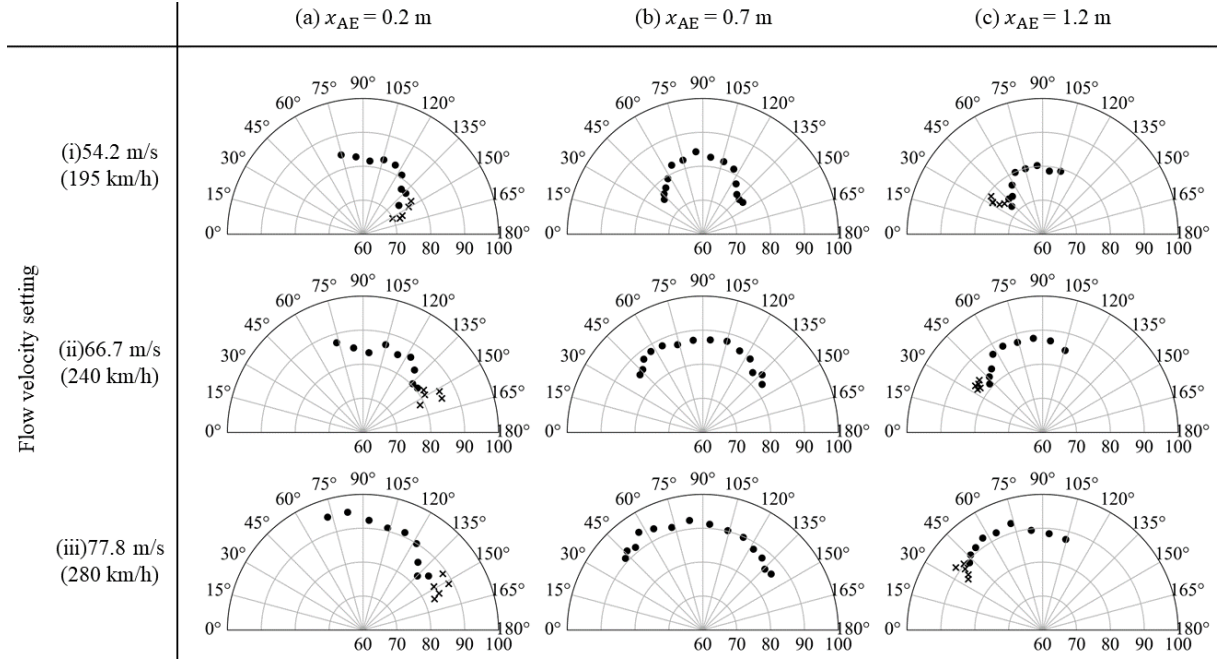


Figure 4.6: Measured directivities of a cylinder of an aerodynamic sound source $L_{\text{dir}}(\theta)$ [dB] at three different positions with three different flow velocity settings. (The influence of the shear layer was corrected and the measured data plotted with $\times$ marks were excluded from an analysis of amplitude modulation by convection.)

4.3 Amplitude modulation due to convection

Similar to moving sources [81,87], the measured directivities of the source in the wind tunnel consists of two components;

$$L_{\text{dir}}(\theta) \equiv L_{\text{dir}}\left(\frac{\pi}{2}\right) + \Delta L_{\text{source}} + \Delta L_{\text{conv}}. \quad (4.15)$$

where ΔL_{source} [dB] is the source term that depends on the directivity characteristics of the sound source and ΔL_{conv} [dB] is the convection term that depends on convection.

The directivity of the cylinder is modeled as a dipole [51, 81]. To consider sound reflection at the surface of the ground plate, it is assumed that the surface to which the source is attached is an infinite panel; an image source of the aerodynamic source is also assumed. Figure 4.7 shows the geometry of the cylinder $\mathbf{r}_{\text{source,r}}$, an image source of that $\mathbf{r}'_{\text{source,r}}$, and the microphone $\mathbf{r}_{\text{mic,c}}$. The combined sound pressure $p(\theta)$ [Pa] from the two sources at the microphone can be expressed as [81]

$$p(\theta) = \frac{\exp(ik|\mathbf{R}|)}{4\pi|\mathbf{R}|} \cos\left(\frac{\pi}{2} - \theta\right) - \frac{\exp(ik|\mathbf{R}'|)}{4\pi|\mathbf{R}'|} \cos\varphi \quad (4.16)$$

where $\mathbf{R}'$ is a vector from the image source to the microphone and $|\mathbf{R}'|$ [m] can be derived as

$$|\mathbf{R}'| = \sqrt{\left(\frac{\Delta z_{\text{AE}}}{\tan\theta}\right)^2 + (\Delta z_{\text{AE}} + 2d)^2}. \quad (4.17)$$

Here, φ [rad] is the angle between the direction from the image source to the real source and the microphone, written as

$$\varphi = \arcsin\left(\frac{|\mathbf{R}|}{|\mathbf{R}'|} \cos\theta\right). \quad (4.18)$$

By correcting the distance attenuation, ΔL_{source} can be written as

$$\Delta L_{\text{source}} = L_{\text{dir,dipole}}(\theta) - L_{\text{dir,dipole}}\left(\frac{\pi}{2}\right) \quad (4.19)$$

where $L_{\text{dir,dipole}}(\theta)$ [dB] is the directivity of a dipole on a reflective plate which there is no air flow and the SPL of radiated sound is maximum in the vertical direction. $L_{\text{dir,dipole}}(\theta)$ [dB] is obtained as

$$L_{\text{dir,dipole}}(\theta) = 20 \lg |p(\theta)| + 20 \lg |\mathbf{R}|. \quad (4.20)$$

Therefore $\Delta L_{\text{conv.}}$ was determined by substituting Eqs. (4.19) and (4.20) into Eq. (4.15).

Figure 4.8 shows the increase in SPL by convection $\Delta L_{\text{conv.}}$ [dB] of the cylinder measured from the source fixed in the wind tunnel ((b) $x_{\text{AE}} = 0.7$ m) and their regression line. The slope of the line is -3.01 and the standard deviation of the regression is 1.45 dB.

Figure 4.8 also depicts the increase in SPL by source movement $\Delta L_{\text{Doppler}}$ [dB] of the moving source measured in the scaled train model experiment in Chapter 3 and the corresponding regression line. Measured data of $\Delta L_{\text{Doppler}}$ are plotted using Eq. (2.20). The slope of the line is -8.77 and the standard deviation of the regression is 2.46 dB.

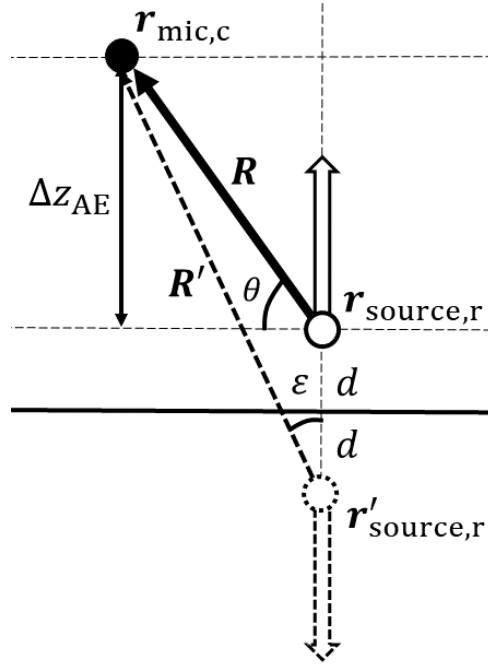


Figure 4.7: Retarded position of a cylinder of an aerodynamic sound source $\mathbf{r}_{\text{source},r}$ and an image sound source of that $\mathbf{r}'_{\text{source},r}$, and the corrected position of a microphone $\mathbf{r}_{\text{mic},c}$.

The value of the slope represents the exponent of acoustic intensity to $\lambda/\lambda_{\text{source}}$ as well as Chapter 3. The slope indicates that the intensity is inversely proportional to approximately the eighth power of $\lambda/\lambda_{\text{source}}$. Comparing the exponents of the acoustic intensity of the aerodynamic sound source obtained from the scaled train model experiment and that obtained from the wind tunnel experiment reveals that the absolute value of the exponent corresponding to source movement is larger than that corresponding to convection. Therefore, the results suggest that an aerodynamic sound yields a larger amplitude modulation induced by source movement than by convection when the apparent wavelength of sound radiated in the air changes by the same proportion.

Figure 4.9 shows the same $\Delta L_{\text{Doppler}}$ [dB] of the moving source as Fig. 4.8, $\Delta L_{\text{conv.}}$ [dB] measured at all the three sound source position, and their regression lines. The slope of the regression line of $\Delta L_{\text{conv.}}$ is -3.43 and the standard deviation of the regression is 1.71 dB. As well as Fig. 4.8, the results suggest that source movement makes an amplitude of an aerodynamic sound change larger than convection. They also suggest that the sound pressure and the acoustic intensity is inversely proportional to approximately the second power and the fourth power of $\lambda/\lambda_{\text{source}}$ because the half of the slope is -1.71 .

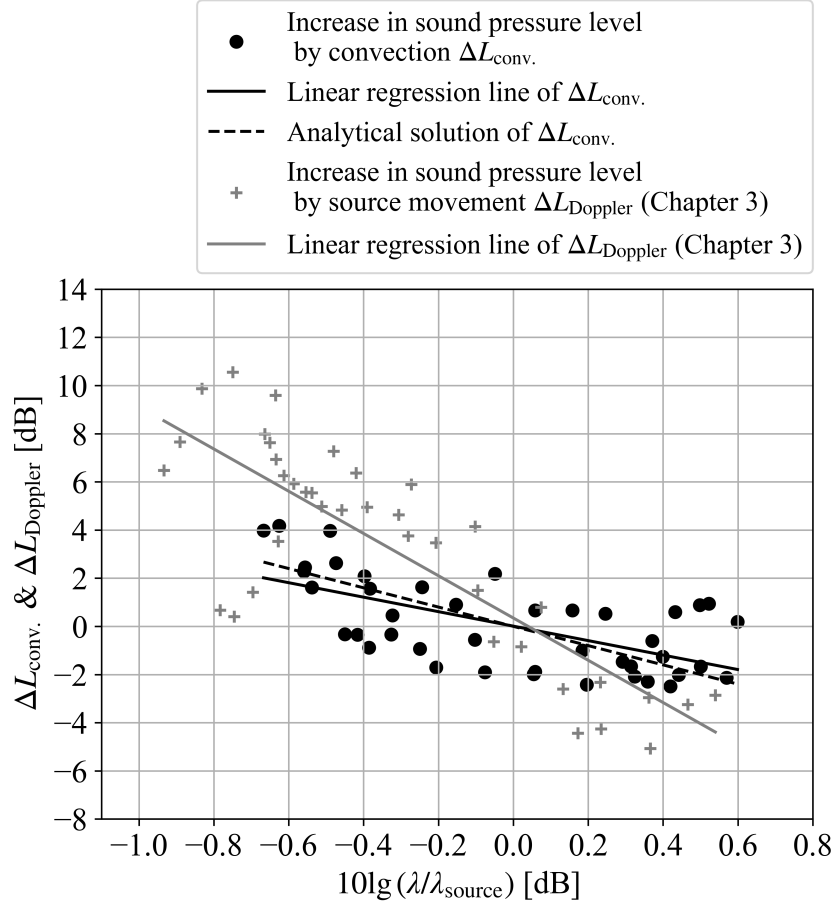


Figure 4.8: Ratios of the apparent wavelength $\lambda/\lambda_{\text{source}}$ of the sound radiated from a cylinder of an aerodynamic sound source and increases in SPL of the source by convection $\Delta L_{\text{conv.}}$ [dB] measured in a wind tunnel experiment ((b) $x_{\text{AE}} = 0.7$ m) and by source movement $\Delta L_{\text{Doppler}}$ [dB] measured in a scaled train model experiment in Chapter 3.

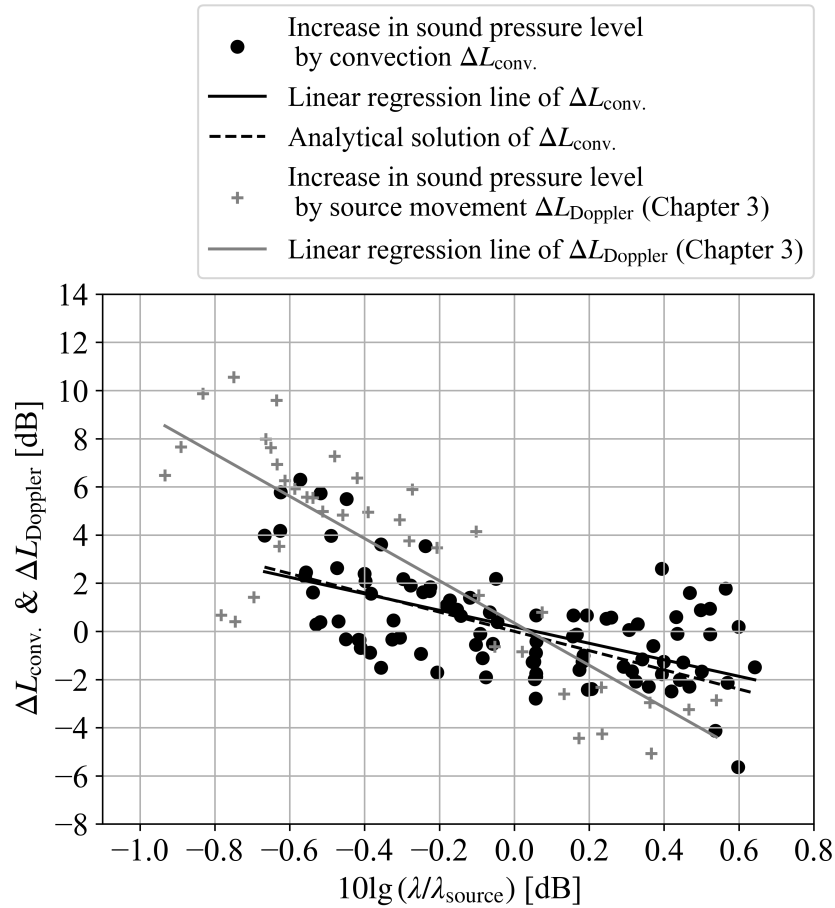


Figure 4.9: Ratios of the apparent wavelength $\lambda/\lambda_{\text{source}}$ of the sound radiated from a cylinder of an aerodynamic sound source and increases in SPL of the source by convection $\Delta L_{\text{conv.}}$ [dB] measured at all the three sound source position in a wind tunnel experiment and by source movement $\Delta L_{\text{Doppler}}$ [dB] measured in a scaled train model experiment in Chapter 3.

4.4 Discussion

According to Eq. (2.15), the acoustic intensity of the sound is inversely proportional to the fourth power of $\lambda/\lambda_{\text{source}}$ because the sound pressure p is inversely proportional to the second power of that from Eq. (2.20), analytically. Figure 4.8 and Figure 4.9 also depict the dashed lines which indicate the analytical solution and are expressed as

$$\Delta L_{\text{conv.}} = -4 \times 10 \lg \left(\frac{\lambda}{\lambda_{\text{source}}} \right). \quad (4.21)$$

These two figures show that the deviation of the slope of the linear regression line of $\Delta L_{\text{conv.}}$ from the analytical slope can be within the range of data variability in the experiment and that the slope of the regression line in Fig. 4.9 is closer to -4 than the slope of the regression line in Fig. 4.8. Thus the intensity is supposed to be inversely proportional to the fourth power of $\lambda/\lambda_{\text{source}}$ and proportional to the fourth power of D_f from Eq. (2.20).

However, the results of the scaled train model experiment in Chapter 3 showed that the acoustic intensity of radiated sound is not proportional to the fourth power but approximately the eighth power of D_f . Their results show good agreement with those predicted by Wright [41] in a theoretical study, which means that the sound pressure of aerodynamic sound observed by a stationary observer is proportional to the $3+P$ th power of D_f , where P is the order of the multipole ($P=0, 1$, or 2 for a monopole, dipole, or quadrupole sound source, respectively).

These good agreements are likely attributable to the source strength F'_j being the partial derivative rather than the material derivative of F_j . F'_j does not represent the time derivative of the external force at the moving source position, but the instantaneous value of the time derivative when the point source is at a fixed position in the trajectory of the source. Even if the sound source moves at a constant speed, the source amplitude is not constant with respect to time; as a result of time fluctuations, the amplitude of the radiated sound also changes depending on the time or direction of the radiated sound. However, in the wind tunnel experiment, the source position is fixed in the flow which maintains a steady state. The time derivative of the external force at the source position becomes the time derivative of that at the fixed position where the source exists. The exponent corresponding to the sound radiated from the source measured in the experiment is then not substantially different from that predicted by Eq. (2.15). Therefore, the difference in the exponent of the sound radiated from the source predicted in the theoretical

study of Wright [41] and that predicted by Eq. (2.15) was confirmed experimentally as the difference of amplitude modulation of the radiated sound caused by source movement and convection.

Notably, the standard deviation between the measured $\Delta L_{\text{Doppler}}$ or $\Delta L_{\text{conv.}}$ and the linear regression line of data acquired in both experiments was larger than 1.0 dB, which is larger than the corresponding standard deviation in the experimental study by Norum *et al.* [77]. This larger standard deviation might be attributable to the height difference between the source and the microphone Δz_{AE} not being sufficiently larger than the wavelength of aerodynamic sound.

4.5 Summary

The influence of source movement or convection on the amplitude of radiated aerodynamic sound is investigated experimentally. The directivities of a simplified aerodynamic sound source were measured at a fixed position out the flow in a wind tunnel at various flow velocities at low Mach number. The source was radiating aeolian tone sound that was a dipole component of aerodynamic sound and was caused by pressure fluctuations.

The results show that, because of convection, the acoustic intensity of radiated sound increases approximately in inverse proportion to the fourth power of the ratio of the apparent wavelength in the flow to the original wavelength.

The amplitude modulations obtained by the wind tunnel measurements were compared with the modulation due to sound source movement. The results suggest that an aerodynamic sound yields a larger amplitude modulation because of source movement rather than convection when the apparent wavelength of radiated sound in the atmosphere changes by the same proportion. Therefore, the directivity of an aerodynamic sound source observed in wind tunnel experiments, which includes the influence of amplitude modulation due to convection, does not directly represent the one when the source is actually moving, but rather shows an under-representation of amplitude modulation compared to the moving source. Similarly, radiated SPL of the aerodynamic sound estimated in wind tunnel experiments may be underestimated compared to the level of the same source moving in the stationary air.

Chapter 5

Influence of source movement on noise metrics

5.1 Introduction

Up to the previous chapter, amplitude modulation of a single vibrational and aerodynamic source has been discussed.

There have been studies of the influence of sound source movement on radiated sound characteristics from moving sound sources based on the analytical solution of the sound pressure field of a uniformly moving vibrational point source analytically derived by Morse and Ingard [50]: the launching experiment in Chapter 3 showed good agreement between the experimental result and the analytical result of amplitude modulation. For instance, Doi *et al.* [93] clarified how high-speed source movement and the time constant of measurement equipment affect the maximum SPL at the receiver and the source position at the time when the maximum sound pressure is recorded. Tsuru *et al.* [94] performed numerical simulations of sound waves generated by moving sources and auralized the resulting sound waves. Buret [95] investigated the reflection characteristics of sound waves on the ground while considering frequency and amplitude modulation due to source movement.

On the other hand, Duhamel [96] proposed a method to obtain the solution of a three-dimensional sound field by performing an integral transform in the transverse direction on a two-dimensional sound field numerically calculated using the boundary element method. This approach is particularly effective in reducing computation time for acoustic simulations in spaces where the cross-section of obstacles, such as noise barriers, remains uniform in a specific direction. Other studies utilizing this method to analyze outdoor acoustic propagation in the presence of noise barriers include Chandler-Wilde [97]. Jean [98] ap-

plied this method to the analysis of three-dimensional sound fields generated by railway noise. Sakamoto [99] applied this method to a two-dimensional sound field obtained using the finite-difference time-domain (FDTD) method. Duhamel [96] also applied the integral transform to a sound source moving in the direction perpendicular to a cross-section of a noise barrier, causing frequency and amplitude modulation. Using the transform, Ogata *et al.* [100] estimated the insertion loss of noise barriers for moving sound sources. Note that their method to calculate frequency shifts due to the Doppler effect is only valid when the speed of sound propagation is significantly larger than the speed of the moving source. Nakajima *et al.* [101] assessed numerical calculation errors in numerical investigation using the transform. They also pointed out that there is confusion between velocity potential and sound pressure in Ref. [96] by Duhamel and that the sound pressure waveform and the velocity potential waveform of a moving source will give different results actually even if normalization is performed, which is reflected in the difference of the exponent of Doppler factor in Eq. (2.10) and Eq. (2.13). Kasess and Waubke [102] examined interpolation methods for discretely sampled data, such as audio files, and analyzed the associated errors to improve computational efficiency when applying this method to three-dimensional sound field calculations using discrete sound source signals.

However, all the previous studies which have been mentioned above in the section consider only a single omnidirectional point source as the sound source model. In contrast, actual transportation noise is generally modeled as a line source or an array of point sources. For example, Harmonoise [8] and CNOSSOS-EU [9] employ a method where traffic flow is modeled with stationary line sources positioned along roads or railways. Transportation noise metrics are then estimated by summing the energy contributions from discretized line source elements. For conventional railways and Shinkansen trains which radiated noise originates from multiple cars moving in succession along the track direction, sound source models have been proposed such as

- a finile line source with directivity [11, 103–107]
- a group of sound sources with directivity in line [108]
- a group of omnidirectional sound sources in line [12, 109]

for railway noise prediction. However, there are few studies that clarify the change of radiated sound characteristics when frequency and amplitude modulation occur in the radiated sound from such sources. L.A.M. van der Heijden and R.J.J.H. van Son [110]

modeled traffic flow as a stationary array of point sources and examined the impact of neglecting the Doppler effect. Their study concluded that for a moving speed of 100 km/h, the influence of the Doppler effect is negligible. However, they did not verify cases where the moving speed reaches several hundred km/h, as seen in Shinkansen and Maglev trains.

Furthermore, while previous chapters have focused on physical changes in sound pressure, actual transportation noise is typically evaluated using the A-weighted SPL which adjusts frequency components to reflect human auditory. Because the frequency of radiated sound at the observer changes as the source approaches and passes by, the A-weighted SPL also varies accordingly. As a result, in addition to the amplitude modulation described in the previous chapters, frequency modulation of the radiated sound is also expected to affect the transportation noise evaluation. However, the influence of these phenomena, caused by source movement, on the noise evaluation has not been clarified.

This chapter aims to clarify the changes in noise propagation characteristics caused by source movement by numerically calculating and comparing noise metrics (the peak or mean value in energy of A-weighted sound pressure levels) of transportation noise with and without considering frequency and amplitude modulation. Numerical investigations are conducted using simplified transportation noise sources as a sound source group which consists a series of point sources moving along a straight track.

In this chapter, computing noise metrics is mainly performed for railway noise. However, to investigate the effects of frequency and amplitude modulation in sound propagation, the velocity dependencies of the acoustic power of the sources are not considered; the acoustic power of the sources are assumed to be constant regardless of source velocity.

Note that this chapter is mainly based on Ref. [71].

5.2 Radiated sound from a moving source

It is supposed that a sound source group is moving at velocity V [m/s] along an infinite straight track parallel to z -axis (see Fig. 5.1). The track is located at $(x, y) = (x_0, y_0)$. The distance from the track to a receiver $R(x, y, 0)$ is $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$ [m]. The source group consists of N incoherent point sources (monopole volume sources). The top and the end of the sound source group are defined as $S_{\text{top}}(x_0, y_0, Vt)$ and $S_{\text{end}}(x_0, y_0, Vt - L)$ respectively, where t [s] is time and L [m] is length of the group as shown in the figure.

Interval from S_{top} to S_{end} is divided into N sections and a source is located at the center of each section. Thus, n th source S_n is located at $(x_0, y_0, z_{S_n}) = (x_0, y_0, Vt + z_n)$ where z_n [m] is z -coordinate of S_n and expressed as

$$z_n = -\frac{L(2n-1)}{2N}. \quad (5.1)$$

As a sound signal from each source, volume velocity of each one is defined as $a(t) = \tilde{a} \exp(-i\omega_{\text{source}}t)$ [m^3/s], where $\tilde{a}$ [m^3/s] is amplitude of volume velocity and ω_{source} is the signal frequency of each source.

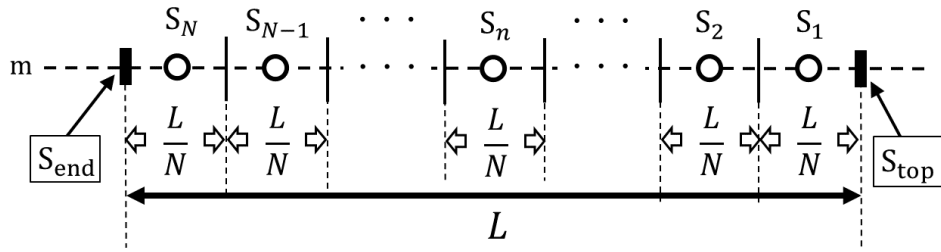
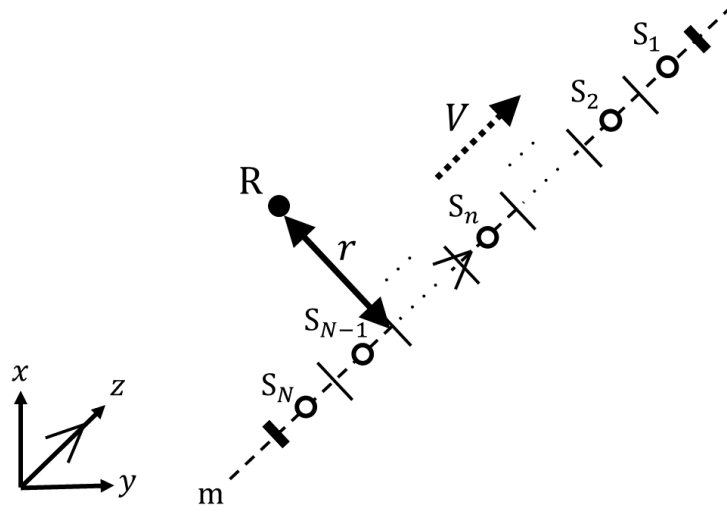
(a) Moving sources $S_1, S_2, \dots, S_N$ with equal distance.(b) A moving source group and a receiver R .

Figure 5.1: Calculation model.

5.2.1 Radiated sound pressure

Sound pressure p_n [Pa] radiated from S_n is represented as

$$p_n = \rho \frac{\partial \phi_n}{\partial t} \quad (5.2)$$

where $\phi_n(x, y, z, t)$ [m²/s] is velocity potential, which is the solution of the wave equation as (see Eq. (2.8))

$$\frac{1}{c^2} \frac{\partial^2 \phi_n}{\partial t^2} - \nabla^2 \phi_n = a(t) \delta(x - x_0) \delta(y - y_0) \delta(z - z_{S_n}). \quad (5.3)$$

Here, ϕ_n and $a(t)$ are Fourier-transformed with respect to t and z as

$$\Phi_n(x, y, k_z, \omega) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \phi_n \exp(-ik_z z) \exp(i\omega t) dz dt \quad (5.4)$$

and

$$A_{xy,n}(k_z, \omega) = \int_{-\infty}^{\infty} a(t) \exp(-ik_z z_{S_n}) \exp(i\omega t) dt. \quad (5.5)$$

The Fourier transform of Eq. (5.3) with respect to t and z is represented as

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \Phi_n + k_{xy}^2 \Phi_n = -A_{xy,n} \delta(x - x_0) \delta(y - y_0) \quad (5.6)$$

where $k = \omega/c$ [rad/m] is wavenumber and $k_{xy} = \sqrt{k^2 - k_z^2}$. This equation corresponds to the Helmholtz equation in a sound field with a wavenumber k_{xy} , generated by a point source $A_{xy,n}$ located at coordinates $(x, y) = (x_0, y_0)$ in a two-dimensional space. The solution of the equation is $\Phi_n = A_{xy,n} \Phi_{xy,n}(x, y, k_{xy})$ where $\Phi_{xy,n}(x, y, k_{xy})$ is the solution of Eq. (5.6) where $A_{xy,n} = 1$. ϕ_n is the inverse Fourier transform of Φ_n with respect to t and z and obtained as

$$\phi_n = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A_{xy,n}(k_z, \omega) \Phi_{xy,n}\left(x, y, \sqrt{k^2 - k_z^2}\right) \exp(ik_z z) \exp(-i\omega t) dk_z d\omega. \quad (5.7)$$

Here, $A(\omega)$ is the Fourier transform of $a(t)$ with respect to t as

$$A(\omega) = \int_{-\infty}^{\infty} a(t) \exp(i\omega t) dt. \quad (5.8)$$

Using this, $A_{xy,n}$ can be written as

$$A_{xy,n} = \int_{-\infty}^{\infty} a(t) \exp(-ik_z z_n) \exp[i(\omega - k_z V)t] dt = \exp(-ik_z z_n) A(\omega - k_z V) \quad (5.9)$$

because $z_{Sn}(t) = z_n + Vt$, and substituting this into Eq. (5.7),

$$\phi_n = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(\omega - k_z V) \Phi_{xy,n} \left(x, y, \sqrt{k^2 - k_z^2} \right) \exp[ik_z(z - z_n)] \exp(-i\omega t) dk_z d\omega. \quad (5.10)$$

Since $\Phi_{xy,n}$ is the velocity potential in a two-dimensional space constructed in the xy -plane, if the characteristics of the two-dimensional sound field $\Phi_{xy,n}$ are calculated for the case where the sound source moves at a constant velocity, ϕ_n can be obtained solely through frequency synthesis even when $A(\omega)$ (the frequency characteristics of the sound source) change. $A(\omega)$ can be calculated as

$$A(\omega) = \int_{-\infty}^{\infty} \tilde{a} \exp[i(\omega - \omega_{\text{source}})t] dt = 2\pi \tilde{a} \delta(\omega - \omega_{\text{source}}) \quad (5.11)$$

and substituting this into Eq.(5.10),

$$\phi_n = \frac{\tilde{a} \exp(-i\omega_{\text{source}}t)}{2\pi} \int_{-\infty}^{\infty} \Phi_{xy,n} \left(x, y, \sqrt{\left(\frac{\omega_{\text{source}} + k_z V}{c} \right)^2 - k_z^2} \right) \exp[ik_z(z - z_n - Vt)] dk_z. \quad (5.12)$$

$\Phi_{xy,n}(x, y, k)$ is formed by a single point source in a two-dimensional free sound field in the xy -plane and represented as

$$\Phi_{xy,n}(x, y, k) = \frac{i}{4} H_0^{(1)}(kr) \quad (5.13)$$

where $H_0^{(1)}$ is the 0th-order Hankel function of the first kind. Substituting this into Eq. (5.12),

$$\phi_n = \frac{\tilde{a} \exp(-i\omega_{\text{source}}t)}{2\pi} \int_{-\infty}^{\infty} \frac{i}{4} H_0^{(1)} \left(r \sqrt{\frac{(\omega_{\text{source}} + k_z V)^2}{c^2} - k_z^2} \right) \exp[ik_z(z - z_n - Vt)] dk_z. \quad (5.14)$$

Applying the integral transform as $k_z = uk'_z + v$; $u = c/\sqrt{c^2 - V^2}$; $v = V\omega_S/(c^2 - V^2)$, using the equations as [111]

$$\frac{\exp(iK\sqrt{r^2 + z^2})}{4\pi\sqrt{r^2 + z^2}} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{i}{4} H_0^{(1)} \left(r\sqrt{K^2 - \kappa^2} \right) \exp(i\kappa z) d\kappa \quad (5.15)$$

and

$$\left(0 < \arg \left(\sqrt{K^2 - \kappa^2} \right) < \pi, 0 < r \right) \quad (5.16)$$

where K is a certain real number and κ is an integral variable, ϕ_n at $z = 0$ can be described as

$$\phi_n = \frac{\tilde{a} \exp(-i\varphi)}{4\pi r'}; \quad (5.17)$$

$$r' = \sqrt{(1 - M^2)r^2 + (-z_n - Vt)^2}; \quad (5.18)$$

$$\varphi = \frac{\omega_{\text{source}} t}{1 - M^2} + \left(\frac{\omega_{\text{source}}}{c} \right) \frac{M z_n - r'}{1 - M^2}. \quad (5.19)$$

Using Eq. (5.2), p_n can be determined as

$$p_n = -\frac{\rho \tilde{a} \exp(-i\varphi)}{4\pi r'} \left(i \frac{\partial \varphi}{\partial t} + \frac{1}{r'} \frac{\partial r'}{\partial t} \right) \quad (5.20)$$

and approximated as

$$p_n \approx -i \frac{\partial \varphi}{\partial t} \frac{\rho \tilde{a} \exp(-i\varphi)}{4\pi r'} \quad (5.21)$$

based on the approximation as (see Appendix B)

$$i \frac{\partial \varphi}{\partial t} + \frac{1}{r'} \frac{\partial r'}{\partial t} \approx i \frac{\partial \varphi}{\partial t}. \quad (5.22)$$

5.2.2 A-weighted SPL

The frequency ω'_n of radiated sound at R from S_n is the time derivative of the phase of the radiated sound pressure and represented as

$$\omega'_n = \frac{\partial \varphi}{\partial t} = \frac{\omega_{\text{source}}}{1 - M^2} \left(1 - \frac{M z_{S_n}}{\sqrt{(1 - M^2)r^2 + z_{S_n}^2}} \right). \quad (5.23)$$

The root mean square (RMS) value $\bar{p}_n$ [Pa] and $\bar{p}_{A,n}$ [Pa] of p_n and A-weighted instantaneous sound pressure $p_{A,n}$ [Pa] at R from S_n have the relationship as [112]

$$10 \lg \left(\frac{\bar{p}_{A,n}}{\bar{p}_n} \right)^2 = 10 \lg \left[\frac{A_w(f'_n)}{A_w(1000)} \right]^2 \quad (5.24)$$

and

$$A_w(f) = \frac{f_4^2 f^4}{(f^2 + f_1^2) \sqrt{f^2 + f_2^2} \sqrt{f^2 + f_3^2} (f^2 + f_4^2)}, \quad (5.25)$$

where $f'_n = \omega'_n / 2\pi$ [Hz]; $f_1 = 20.60$ Hz; $f_2 = 107.7$ Hz; $f_3 = 737.9$ Hz; $f_4 = 12194$ Hz.

Since the radiated sound from each source of the source group are incoherence, the A-weighted SPL L'_A [dB] radiated from the entire sound source group considering sound

source movement, is energy sum of all the A-weighted SPLs of the sources in the source group, which is represented as

$$L'_A = 10 \lg \left(\frac{\bar{p}_A}{p_0} \right)^2 \quad (5.26)$$

and

$$\bar{p}_A^2 = \sum_{n=1}^N \bar{p}_{A,n}^2 = \sum_{n=1}^N \left[\bar{p}_n \frac{A_w(f'_n)}{A_w(1000)} \right]^2, \quad (5.27)$$

where $\bar{p}_A$ [Pa] is the RMS value of the A-weighted pressure at R from the entire source group and $p_0 = 20 \mu\text{Pa}$.

5.2.3 Time weighting S (slow)

A-weighted SPL $L_{AS}(t)$ [dB] with time weighting S (slow) can be obtained as [112]

$$L_{AS}(t) = 10 \lg \left[\frac{1}{p_0^2} \frac{1}{\tau_S} \int_{-\infty}^t p_A^2(\xi) \exp \left(-\frac{t-\xi}{\tau_S} \right) d\xi \right] \quad (5.28)$$

where $\tau_S = 1 \text{ s}$ is the time constant for the time weighting S (slow); p_A [Pa] is A-weighted instantaneous sound pressure from the entire source group; ξ is a dummy variable of time integration. This is rewritten as

$$L_{AS}(t) = 10 \lg \left(\frac{p_{AS}^2}{p_0^2} \right) \quad (5.29)$$

and

$$p_{AS}^2(t) = \frac{1}{\tau_S} \int_{-\infty}^t p_A^2(\xi) \exp \left(-\frac{t-\xi}{\tau_S} \right) d\xi. \quad (5.30)$$

In computing at discrete times, provided that $p_A^2(\xi) = p_A^2[t] = \text{const.}$ at $t - \Delta t < \xi \leq t$ where Δt [s] is time step, $p_{AS}^2[t]$ is determined as

$$p_{AS}^2[t] = p_{AS}^2[t - \Delta t] \exp \left(-\frac{\Delta t}{\tau_S} \right) + p_A^2[t] \left[1 - \exp \left(-\frac{\Delta t}{\tau_S} \right) \right]. \quad (5.31)$$

5.2.4 Equivalent continuous sound level

Equivalent continuous sound level (time-averaged sound level) $L_{Aeq,T}$ [dB] is time averaged A-weighted SPL during measurement time interval $T (= t_2 - t_1)$ [s] and can be obtained as [10, 112]

$$L_{Aeq,T} = 10 \lg \left(\frac{1}{p_0^2} \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} p_A^2(\xi) d\xi \right) \quad (5.32)$$

where t_1 [s] and t_2 [s] are the beginning and ending time of T . In calculating at discrete times, this is computed using $p_A [t]$ at equal time steps from t_1 to t_2 as

$$L_{\text{Aeq},T} = 10 \lg \left(\frac{1}{p_0^2} \frac{1}{N_t} \sum_t p_A^2 [t] \right) \quad (5.33)$$

where N_t is the number of discrete times from t_1 to t_2 .

5.2.5 Doppler effect

Because of the Doppler effect, the frequency of the radiated sound from the sound source at the receiver change from the original source frequency.

Let θ be the azimuth angle of the receiver R as seen from the sound source S_n in the direction of propagation. This angle θ changes due to the movement of S_n during the time that it takes for the sound wave emitted from S_n to reach R.

If this change is ignored and θ is assumed to be constant, the frequency ω_n of the radiated sound from S_n at R can be obtained as

$$\omega_n = \omega_{\text{source}} \frac{c}{c - V \cos \theta} = \omega_{\text{source}} \left(1 + M \frac{z_{S_n}}{\sqrt{r^2 + z_{S_n}^2}} \right)^{-1}. \quad (5.34)$$

Figure 5.2 shows the changes of (a) the ratio of ω'_n and ω_n to ω_{source} . When frequency modulation calculated by Eq. (5.23) which considers the variation of θ , the time when sound frequency at the receiver shifts from high to low is delayed and the delay becomes longer as the source velocity increases.

5.2.6 Amplitude modulation

A-weighted SPL from the sound source group moving at constant speed computed considering and ignoring frequency and amplitude modulation due to source movement, is compared.

The A-weighted SPLs $L_{A,n}(t)$ [dB] and $L_A(t)$ [dB] of S_n and the entire source group computed ignoring source movement are obtained as

$$L_{A,n}(t) = L_{wA} - 10 \lg [4\pi d_n^2(t)] \quad (5.35)$$

and

$$L_A(t) = 10 \lg \left(\sum_{n=1}^N 10^{\frac{L_{A,n}(t)}{10}} \right) \quad (5.36)$$

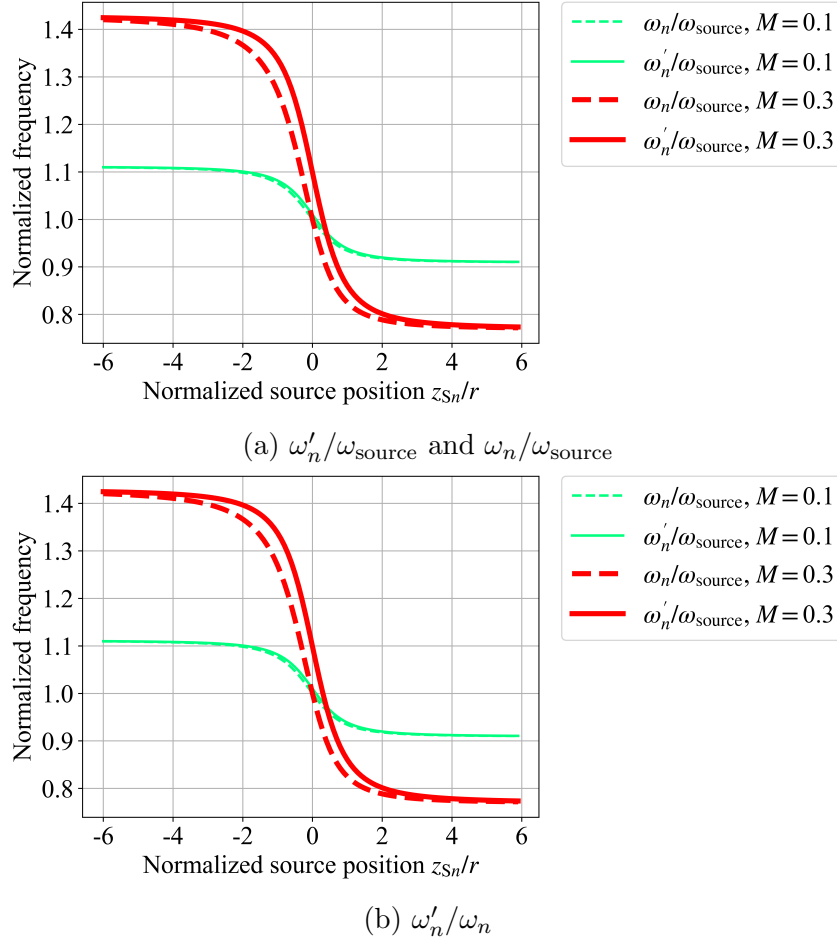


Figure 5.2: Doppler effect due to a single source movement ($M = 0.1, 0.3$). When azimuth angle variation in time is considered, the time when calculated frequency of the radiated sound drops delay.

where $d_n(t)$ [m] is the distance from S_n and R derived as

$$d_n(t) = \sqrt{r^2 + z_{Sn}^2} = \sqrt{r^2 + (Vt + z_n)^2} \quad (5.37)$$

and L_{wA} [dB] is the A-weighted sound power level (PWL) of a single sound source of the source group. Replacing L_{wA} with the PWL L_w [dB] of the single sound source, the SPLs $L_{p,n}(t)$ [dB] and $L_p(t)$ [dB] of S_n and the entire source group computed ignoring source movement are also obtained as

$$L_p(t) = 10 \lg \left(\sum_{n=1}^N 10^{\frac{L_{p,n}(t)}{10}} \right) \quad (5.38)$$

and

$$L_{p,n}(t) = L_w - 10 \lg [4\pi d_n^2(t)]. \quad (5.39)$$

Substituting $M = 0$ and $z_n = 0$ into Eq. (5.18)-(5.20), p_n can be derived as

$$p_n = -\frac{\rho \tilde{a} \exp(-i\varphi)}{4\pi r'} \left(i \frac{\partial \varphi}{\partial t} + \frac{1}{r'} \frac{\partial r'}{\partial t} \right) = -i\omega_{\text{source}} \frac{\rho \tilde{a}}{4\pi r} \exp \left[-i \left(\omega_{\text{source}} t - r \frac{\omega_{\text{source}}}{c} \right) \right] \quad (5.40)$$

because $r' = \sqrt{r^2} = r$ and $\varphi = \omega_{\text{source}} t - r\omega_{\text{source}}/c$. The RMS value $\bar{p}_n$ [Pa] of p_n is obtained as $\bar{p}_n = f_{\text{source}} \rho \tilde{a} / 2\sqrt{2}r$ where $f_{\text{source}} = \omega_{\text{source}} / 2\pi$ [Hz]. Using Eq. (5.37)(5.39),

$$L_{p,n}(t) = L_w - 10 \lg(4\pi r^2) = 10 \lg \left(\frac{f_{\text{source}} \rho \tilde{a}}{2\sqrt{2}p_0 r} \right)^2. \quad (5.41)$$

Therefore, the relationship between the volume velocity $\tilde{a}$ and the PWL L_w is derived as

$$L_w = 10 \lg \left[\frac{\pi}{2} \left(\frac{f_{\text{source}} \rho \tilde{a}}{p_0} \right)^2 \right], \quad (5.42)$$

$$\therefore \tilde{a} = \frac{p_0}{f_{\text{source}} \rho} \sqrt{\frac{2}{\pi} 10^{\frac{L_w}{10}}} \quad (5.43)$$

In this chapter, all the calculation is performed at $\rho = 1.293 \text{ kg/m}^3$, and $c = 340 \text{ m/s}$. The length of the sound source group L is set as 400 m, which is equivalent to the train length of commonly used 16-car high-speed railway vehicles such as the 0 Series, 100 Series, 100N Series, 200 Series, 300 Series, 500 Series, 700 Series, and E4 Series of the Shinkansen [85].

Figure 5.3 shows the computed L'_A and L_A where the source velocity is 300 km/h ($M = 0.245$), $r = 7.5 \text{ m}$, $L_{wA} = 120 \text{ dB}$, and $N = 16$ (with each sound source spaced 25 m apart). Figure 5.3(a) represents the calculated L'_A and L_A , while Figure 5.3(b) shows the difference between the two levels $\Delta L_A (= L'_A - L_A \text{ [dB]})$. Each source of the source group is assumed to be a high-speed railway vehicle sound source, with normalized railway noise spectrum defined as Table 5.1 and Fig. 5.4 by the EN standard 16272-3-1:2012 [113]. L'_A was obtained by applying a 5 ms time-weighting to the calculated sound pressure waveform. Previous studies [93, 100] have shown that for a single moving sound source, the maximum A-weighted SPL increases, and this peak occurs just before the source passes directly in front of the receiver. Additionally, Tsuru *et al.* [94] has demonstrated that when considering the source movement, the calculated level increases just before each source passes directly in front of R and decreases after passing compared to the level without considering the movement. They were also confirmed in the case of multiple sound sources.

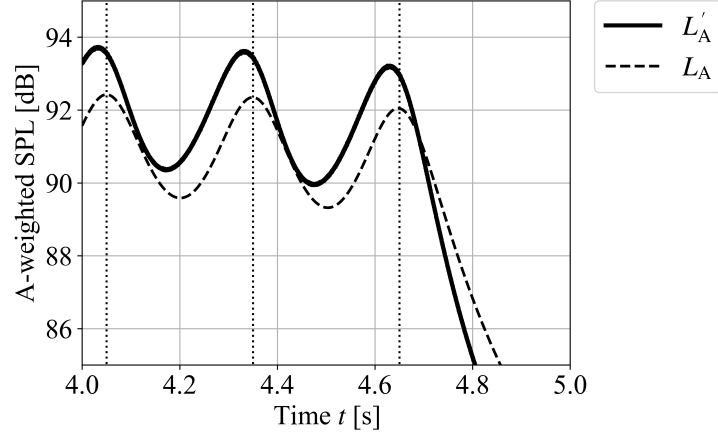
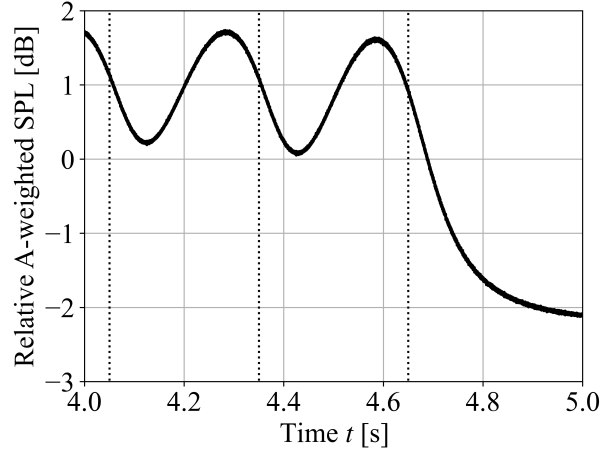
(a) L'_A and L_A (b) ΔL_A

Figure 5.3: Computed A-weighted SPL L'_A [dB] and L_A [dB], and the level difference ΔL_A [dB] (source velocity: 300 km/h ($M = 0.245$), $r = 7.5$ m, $L_{wA} = 120$ dB, $N = 16$, source interval: 25 m). When frequency and amplitude modulation is considered, the maximum A-weighted SPL is observed just before the time when each source is at the closest position from the receiver shown by vertical dotted lines.

Table 5.1: Normalized railway noise spectrum [113].

centre frequency [Hz]	1/3 octave bands level [dB]
100	-27
125	-25
160	-23
200	-21
250	-19
315	-17
400	-15
500	-13
630	-12
800	-11
1000	-10
1250	-9
1600	-9
2000	-9
2500	-9
3150	-10
4000	-13
5000	-17

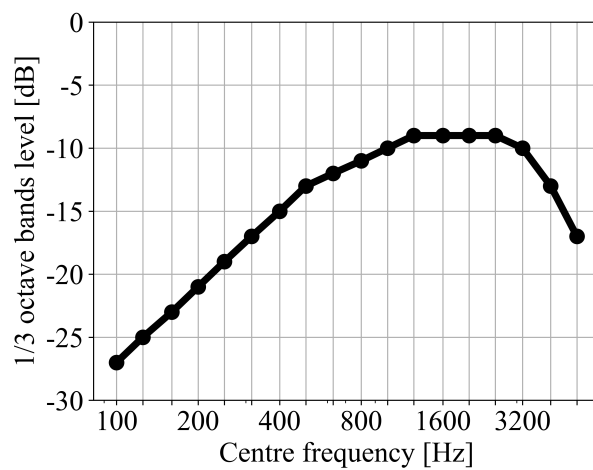


Figure 5.4: Normalized railway noise spectrum [113].

5.3 Change of noise metrics

The following noise metrics are computed with and without considering the frequency and amplitude modulation induced by source movement, so that the effects on these metrics are examined.

- Maximum A-weighted SPL $L_{A\max}$ [dB] (without time weighting).
- Maximum A-weighted SPL $L_{AS\max}$ [dB] with time weighting S (slow).
- A-weighted equivalent continuous SPL $L_{Aeq,Tp}$ [dB] on the pass-by time T_p [s] [114].

$L_{A\max}$ and $L_{AS\max}$ is determined as the maximum value of $L_A(t)$ [dB] and $L_{AS}(t)$. $L_{AS\max}$ is the noise metrics used in measuring and evaluating the Shinkansen trains according to the “Environmental Quality Standards for Shinkansen Super-express Railway Noise” in Japan [115], which is established by the Environmental Agency in 1975 [116] in order to control the noise of the Shinkansen railway lines. In computing $L_{Aeq,Tp}$, the beginning and ending time t_1 and t_2 of T_p are defined as the time when S_{Top} and S_{End} reach in front of the receiver at $(x_0, y_0, 0)$. Then $T_p = L/V$ according to Section 5.2.

The metrics without taking source movement into account are calculated using Eqs. (5.35)-(5.37). The levels with considering that are computed according to Sections 5.2.1 to 5.2.2 and using Eq. (5.43) and denoted with a prime symbol (i.e., $L'_{A\max}$, $L'_{AS\max}$, and $L'_{Aeq,Tp}$). The level differences with or without considering source movement are defined as $\Delta L_{A\max}(= L'_{A\max} - L_{A\max})$ [dB], $\Delta L_{AS\max}(= L'_{AS\max} - L_{AS\max})$ [dB], and $\Delta L_{Aeq,Tp}(= L'_{Aeq,Tp} - L_{Aeq,Tp})$ [dB].

5.3.1 Source discretization

To evaluate the influence of source discretization, source division N is increased while keeping A-weighted PWL of the entire sound source group constant until the source group can be approximated to a finite length line source (Fig. 5.5). The value of N that can sufficiently approximate the source group to a finite line source was obtained where source velocity is 100 km/h ($M = 0.082$) and $r = 7.5$ m. Frequency characteristics of the source group are the Normalized railway noise spectrum [113]. The A-weighted PWL was set as 132 dB, which is equivalent to the calculated results in the previous section.

Figure 5.6 shows noise metrics for different source division N for a source group. All the calculated levels decrease as N increases. This is likely because an increase in N

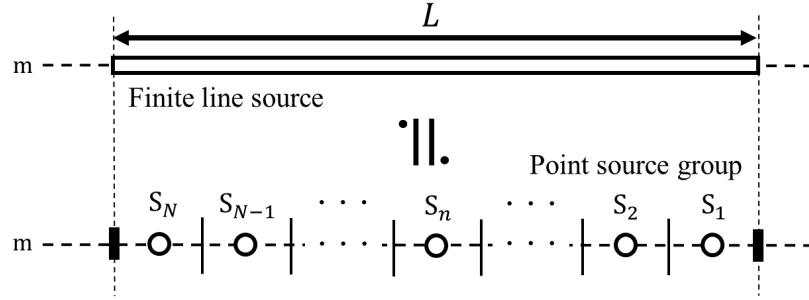


Figure 5.5: The model of finite line source and its calculation model.

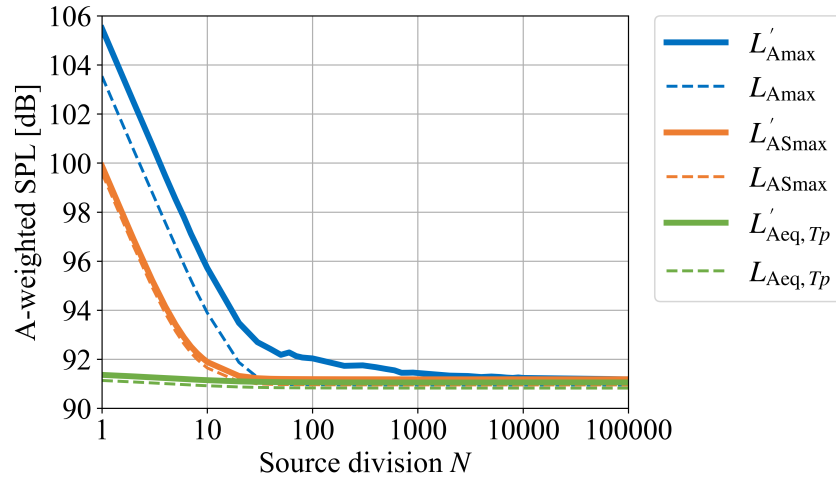


Figure 5.6: Noise metrics for different source division N (source velocity: 100 km/h ($M = 0.082$), $r = 7.5$ m). Calculated levels decrease as the number of source division increases. The levels converge fast in order of $L_{Aeq, Tp}$, L_{ASmax} and L_{Amax} . All the levels converge at about $N = 10000$ within 0.1 dB.

results in a higher density of sound sources within the source group, leading to smaller temporal fluctuations in sound pressure.

Speed of convergence is in order of $L_{\text{Aeq},Tp}$, L_{ASmax} , and L_{Amax} . While L_{ASmax} , L'_{ASmax} , $L_{\text{Aeq},Tp}$, and $L'_{\text{Aeq},Tp}$ all converge within 0.1 dB for approximately $N = 30$, L_{Amax} does not converge within 0.1 dB until around $N = 100$, and L'_{Amax} requires values of N on the order of several thousand to achieve convergence within 0.1 dB. Then all the levels converge at about $N = 10000$ within 0.1 dB.

This indicates that when sound sources are discrete, approximating the source as a finite-length line source may lead to an underestimation of noise metrics. The degree of underestimation follows the order: $L_{\text{Aeq},Tp}$, L_{ASmax} , and L_{Amax} , with the underestimation being most significant for L_{Amax} . Thus, in modeling moving sound sources using this method to evaluate L_{Amax} or L_{ASmax} , it is important not to oversimplify the original sound source distribution.

5.3.2 Change of noise metrics at various velocity and distance from the source track

The variation in noise metrics due to source velocity and the distance from the source track is examined. To eliminate the effects of source discretization on the metrics, the source group was approximated as a finite-length line source. Based on the results from the previous section, numerical calculations were performed with $N = 10000$.

Figure 5.7 depicts the relationship between source velocity and noise metrics under three conditions: (a) $r = 7.5$ m, (b) $r = 25$ m, and (c) $r = 100$ m. Figure 5.9 depicts the relationship between the distance from the source track and noise metrics under three conditions: source velocity of (a) 100 km/h ($M = 0.082$), (b) 300 km/h ($M = 0.245$), and (c) 500 km/h ($M = 0.409$). Both figures indicate that considering frequency and amplitude modulation results in higher levels of the noise metrics.

Figure 5.8 and Figure 5.10 shows the relative A-weight SPLs of the case with considering source movement compared with the one without considering that: ΔL_{Amax} , ΔL_{ASmax} , and $\Delta L_{Aeq,Tp}$. From Fig. 5.8, as source velocity increases, the relative levels increase. At a source velocity of 300 km/h, all the three relative levels reach approximately 1.2 dB across Figs. 5.8(a)–(c). At 500 km/h, they reach 3.0 dB in (a) and (b), while in (c), $\Delta L_{Amax} = 3.3$ dB, $\Delta L_{ASmax} = 3.2$ dB, and $\Delta L_{Aeq,Tp} = 3.0$ dB. From Figure 5.10, no significant dependency of the relative levels (fluctuation of 1.0 dB or more) on distance r was observed. The largest variation in the levels among noise types occurred at $r = 320$ m in condition (c), where $\Delta L_{Amax} = 3.7$ dB, $\Delta L_{ASmax} = 3.6$ dB, and $\Delta L_{Aeq,Tp} = 2.9$ dB.

When a point source moves, wavefronts become compressed in the direction of motion. This results in strong directivity in the direction of movement, increasing the SPL as source speed increases, leading to higher peak SPLs at the receiver [100]. Thus, the level difference between cases with and without modulation is expected to grow with increasing source speed. Although movement alters the directivity, the source remains a point source, meaning that distance attenuation occurs similarly in both cases with and without consideration. As a result, the differences of A-weighted SPLs do not depend significantly on the distance from the source track. In conclusion, the level differences between cases with and without the consideration increase with source velocity but show little dependency on the distance from the source track to the receiver.

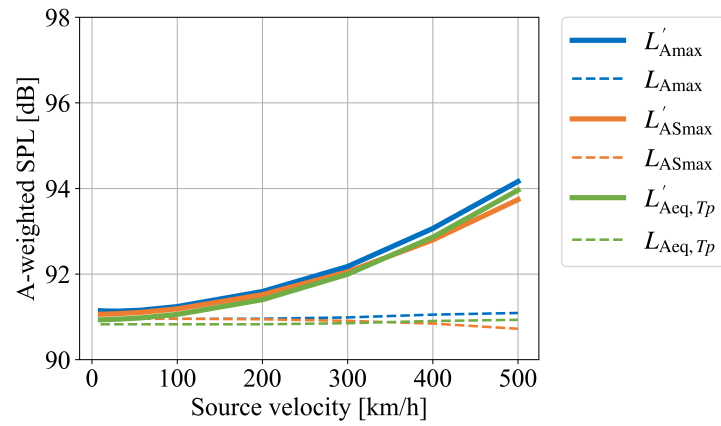
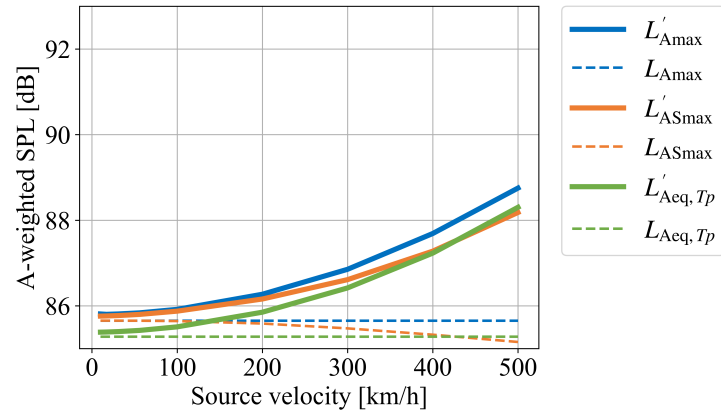
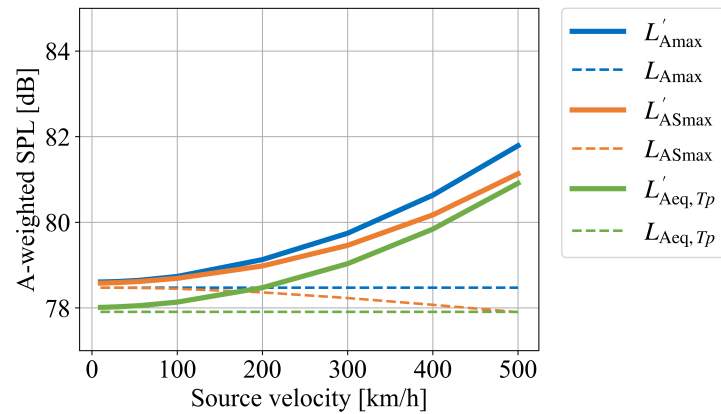
(a) $r = 7.5$ m(b) $r = 25$ m(c) $r = 100$ m

Figure 5.7: Influence of finite line source velocity on noise metrics ($N = 10000$). Calculated levels L_{Amax} , L_{ASmax} and $L_{Aeq, Tp}$, when frequency and amplitude modulation are considered, are larger than the levels without their consideration.

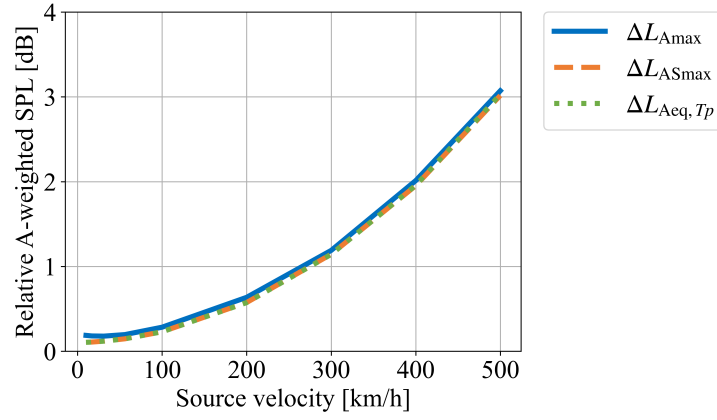
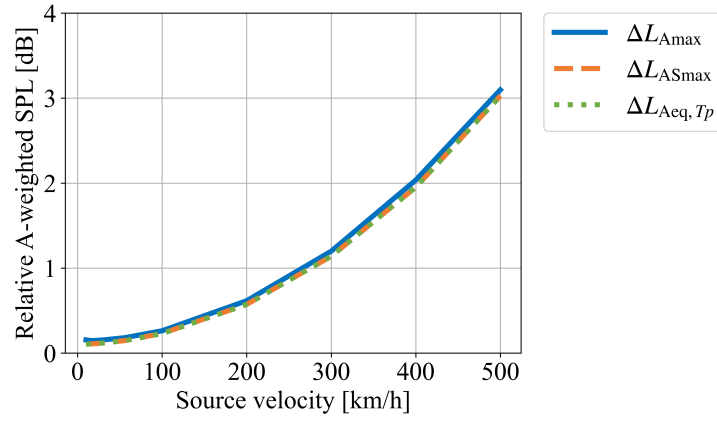
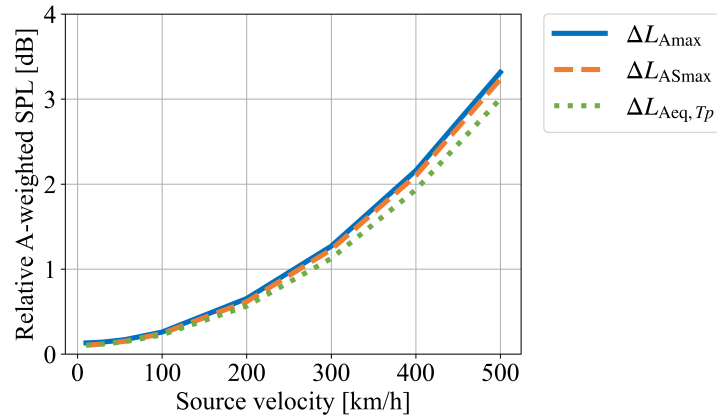
(a) $r = 7.5$ m(b) $r = 25$ m(c) $r = 100$ m

Figure 5.8: Relative A-weighted SPLs ΔL_{Amax} [dB], ΔL_{ASmax} [dB] and $\Delta L_{Aeq, Tp}$ [dB] from Fig. 5.7. The differences of the calculated levels increase monotonically with respect to sound source speed with and without considering frequency and amplitude modulation, and they reach ca. 1.2 dB at a speed of 300 km/h.

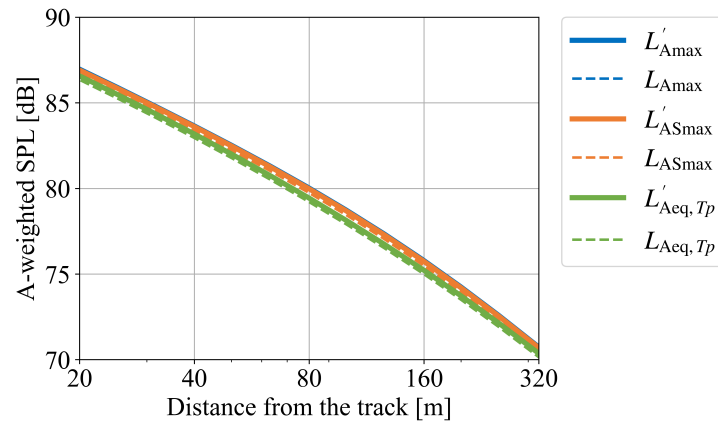
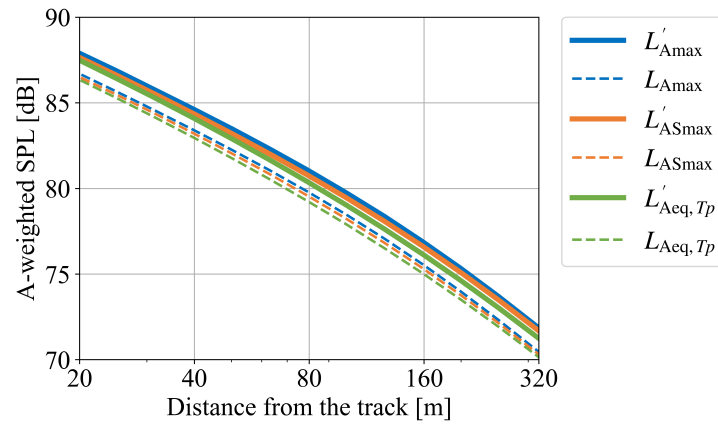
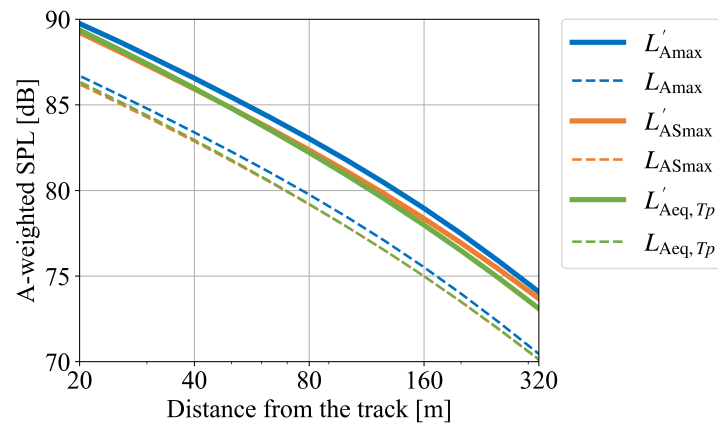
(a) source velocity: 100 km/h ($M = 0.082$)(b) source velocity: 300 km/h ($M = 0.245$)(c) source velocity: 500 km/h ($M = 0.409$)

Figure 5.9: Influence of finite line source velocity on noise metrics ($N = 10000$). Calculated levels L_{Amax} , L_{ASmax} and $L_{Aeq,Tp}$, when frequency and amplitude modulation are considered, are larger than the levels without their consideration.

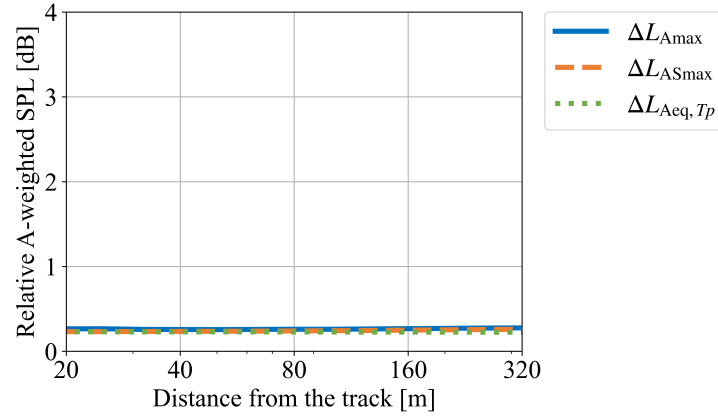
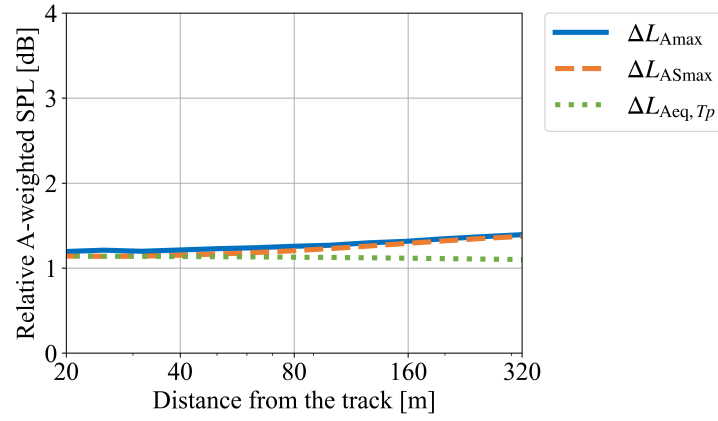
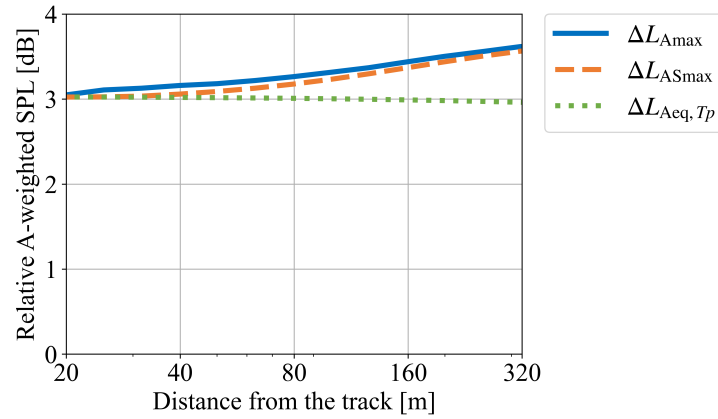
(a) source velocity: 100 km/h ($M = 0.082$)(b) source velocity: 300 km/h ($M = 0.245$)(c) source velocity: 500 km/h ($M = 0.409$)

Figure 5.10: Relative A-weighted SPLs ΔL_{Amax} [dB], ΔL_{ASmax} [dB] and $\Delta L_{Aeq,Tp}$ [dB] from Fig. 5.9. The differences of the calculated levels are independent of distance from the source track between the cases with and without considering frequency and amplitude modulation.

5.3.3 Noise metrics of a sound source group and a finite source line

The effect of source discretization on changes of noise metrics caused by frequency and amplitude modulation is investigated by comparing the calculated noise metrics of a railway vehicle modeled as a sound source group of discrete sources or a finite-length line source. Based on the previous section, $N = 16$ (source spacing of 25 m) is applied for the discrete source model, while $N = 10000$ (source spacing of 0.04 m) is applied for the finite-length line source model.

Figure 5.11 shows results for $r = 7.5$ m. In Fig. 5.11(a), $L_{A\max}$ and $L'_{A\max}$ for $N = 16$ are approximately 1.5 dB and 3.0 dB higher, respectively, than those for $N = 10000$ (hereafter referred to as the finite-length line source model). In Fig. 5.11(b), when the source speed is below 100 km/h ($M = 0.082$), $L_{AS\max}$ and $L'_{AS\max}$ for $N = 16$ are higher than for the finite-length line source. This is likely due to the longer passage time of the sound source, reducing the attenuation effect caused by the time constant processing using τ_s . Beyond this, Figures 5.11(b) and (c) show no significant changes in $L_{AS\max}$, $L'_{AS\max}$, $L_{Aeq,Tp}$, or $L'_{Aeq,Tp}$ between the two models.

Figure 5.12 shows results for a source speed of 300 km/h ($M = 0.245$). Only $L'_{A\max}$ shows an increase of over 1.0 dB in the $N = 16$ model compared to the finite-length line source model. These results indicate that even if A-weighted SPLs ($L'_{AS\max}$, $L'_{Aeq,Tp}$) remain unchanged, differences in source spacing can lead to overestimation or underestimation of $L'_{A\max}$. In such cases, the calculated A-weighted SPLs may not correspond to the actual perceptual characteristics of the noise.

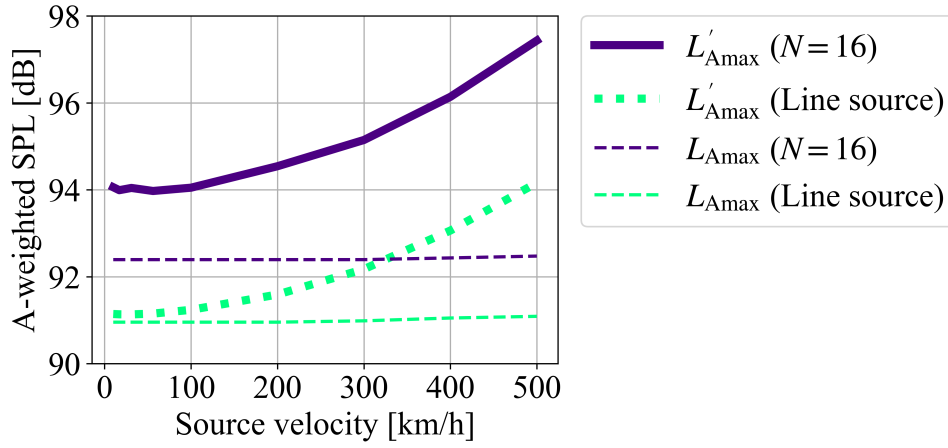
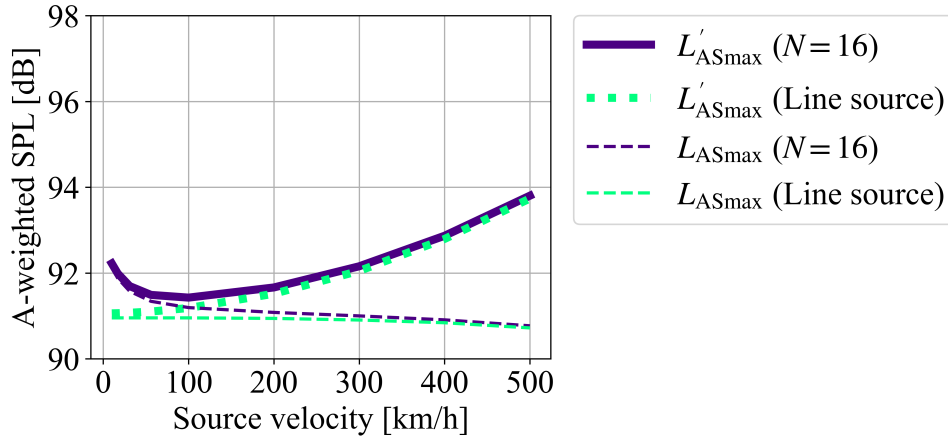
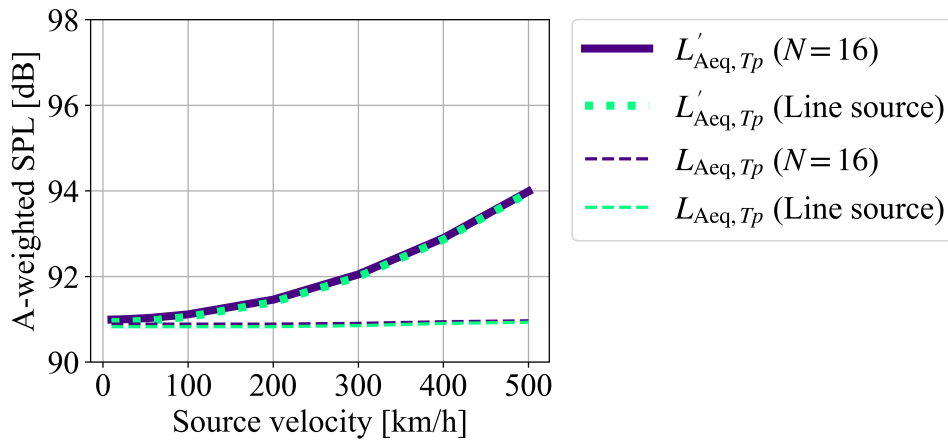
(a) L'_{Amax} and L_{Amax} (b) L'_{ASmax} and L_{ASmax} (c) $L'_{Aeq,Tp}$ and $L_{Aeq,Tp}$

Figure 5.11: Influence of the source division N on noise metrics ($r = 7.5$ m). Calculated levels L_{Amax} and L'_{Amax} for $N = 16$ is larger than the results for $N = 10000$ (finite line source) by ca. 1.5 and 3.0 dB, respectively.

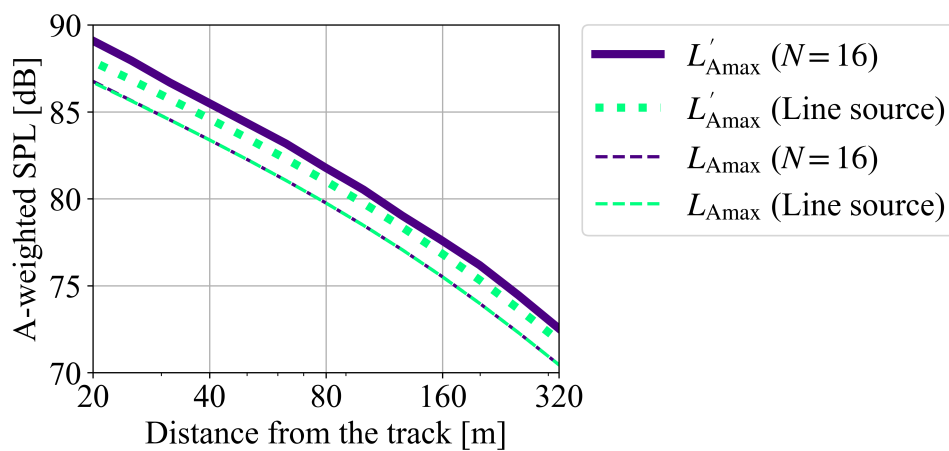
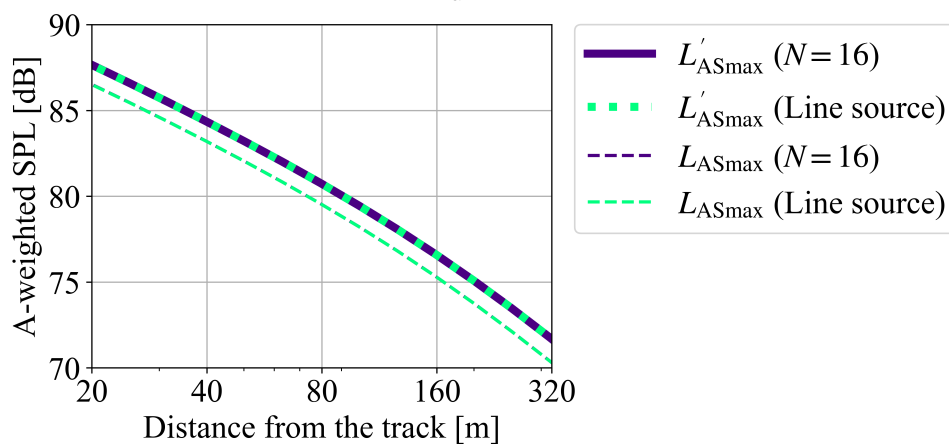
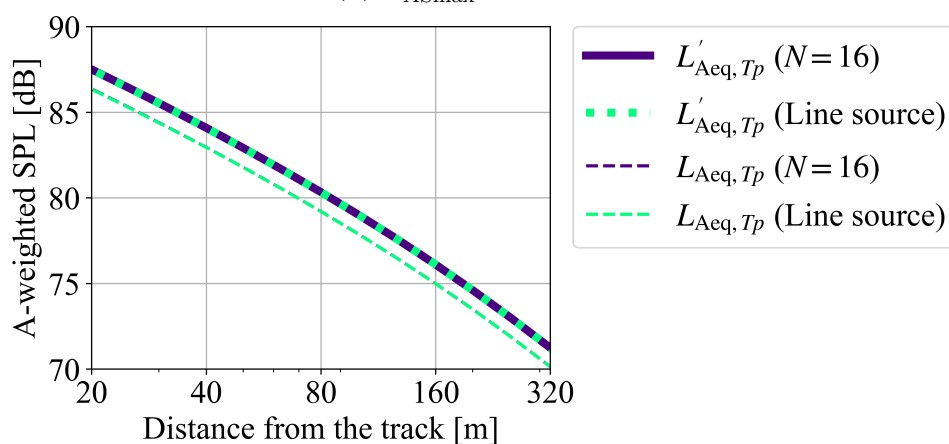
(a) L'_{Amax} and L_{Amax} (b) L'_{ASmax} and L_{ASmax} (c) $L'_{Aeq,Tp}$ and $L_{Aeq,Tp}$

Figure 5.12: Influence of the source division N on noise metrics where source velocity is 300 km/h ($M = 0.245$). Calculated levels L'_{Amax} for $N = 16$ are larger than the results for $N = 10000$ (finite line source) by ca. 1.0 dB.

5.4 Influence of source frequency on relative SPLs

Noise from real vehicles have wideband frequency components. The influence of source frequency on relative SPL or relative A-weighted SPL due to source movement is examined. It is assumed that a finite length line source is emitting a single frequency sound moving at a constant velocity along the track. As well as the previous section, the source is modeled with $N = 10000$ moving at a constant velocity. The A-weighted PWL of the entire source group is maintained at 132 dB while varying the source frequency for the center frequency of 1/3 octave band between 100 Hz and 5000 Hz. The following calculated differences in SPLs without A-weighting are also computed to be compared with the A-weighted SPLs which were mentioned before.

- Maximum SPL $L_{\max}$ [dB]
- Maximum SPL with time weighting S (slow) $L_{S\max}$ [dB]
- Time-averaged SPL L_{eq,T_p} [dB] on the pass-by time T_p

Relative SPLs are obtained and denoted with Δ in the same way as the relative A-weighted SPLs.

Figure 5.13 shows the calculated relative SPLs: $\Delta L_{\max}$, $\Delta L_{S\max}$, and $\Delta L_{\text{eq},T_p}$, and the relative A-weighted SPLs $\Delta L_{A\max}$, $\Delta L_{AS\max}$, and $\Delta L_{A\text{eq},T_p}$ where $M = 0.1, 0.3$ and $r = 25$ m. Figure 5.13(a) revealed that the contribution of source movement results in larger differences in SPLs as source velocity increases while the level differences appear to be almost independent of source frequency. Figure 5.13(b) demonstrates that lower source frequencies lead to larger differences in the A-weighted levels because of the influence of A-weighting. These results indicate that the low-frequency components contribute more significantly to increase the A-weighted levels due to source movement for sources with broadband frequency characteristics.

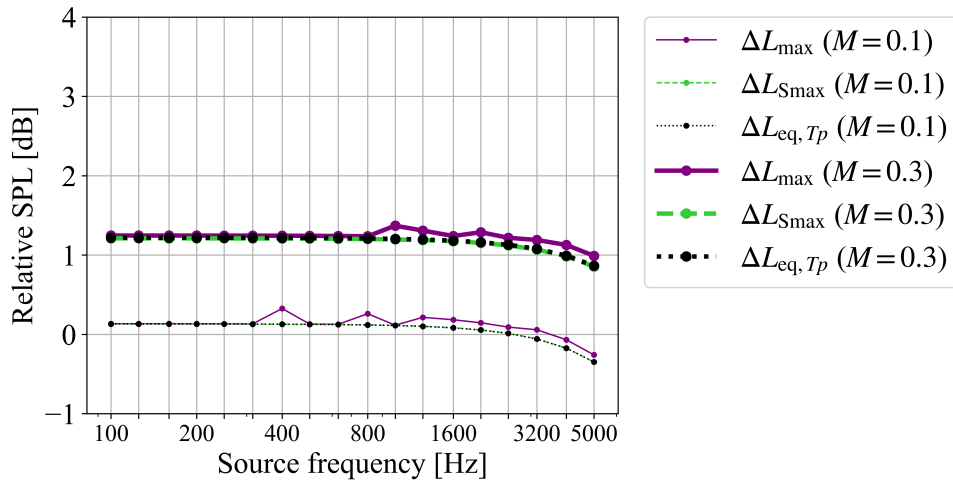
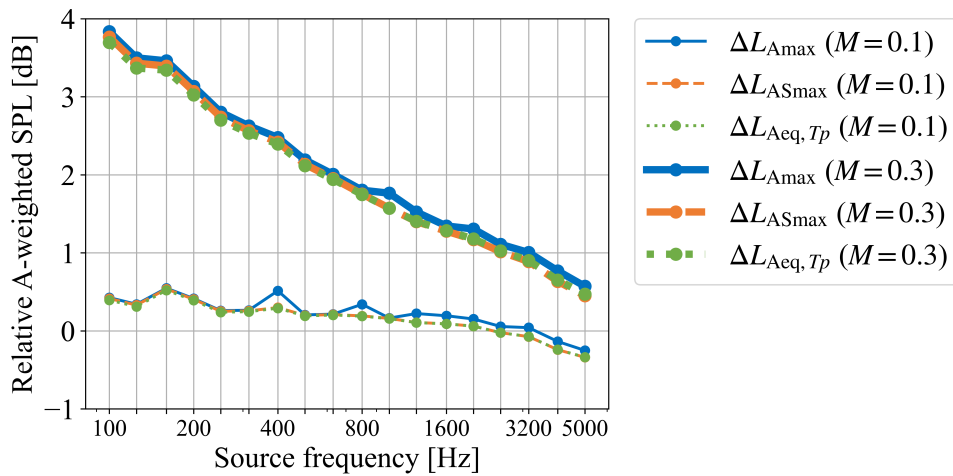
(a) Relative SPLs $\Delta L_{\max}$, $\Delta L_{S\max}$ and $\Delta L_{eq,Tp}$ (b) Relative A-weighted SPLs $\Delta L_{A\max}$, $\Delta L_{AS\max}$ and $\Delta L_{Aeq,Tp}$

Figure 5.13: Relative SPLs and relative A-weighted SPLs for different source frequencies at $r = 25$ m increase with velocity increase. Increase of A-weighted SPL is high at lower frequencies due to its frequency weighting.

5.5 Exponent of relative SPLs

The relationships between the source frequency and the velocity dependence of the amplitude modulation of radiated sound is also presented. It is assumed that a certain relative SPL or A-weighted SPL ΔL [dB] mentioned before increases from $\Delta L(M - \Delta M)$ [dB] to $\Delta L(M + \Delta M)$ [dB] when the Mach number of the moving source changes from $M - \Delta M$ to $M + \Delta M$. Then the increase in the relative A-weighted SPL can be represented as

$$\begin{aligned}\Delta L(M + \Delta M) - \Delta L(M - \Delta M) &\equiv 10 \lg \left(\frac{M + \Delta M}{M - \Delta M} \right)^{N_{\text{exp}}(M)} \\ &= 10 N_{\text{exp}}(M) \lg \left(\frac{M + \Delta M}{M - \Delta M} \right)\end{aligned}\quad (5.44)$$

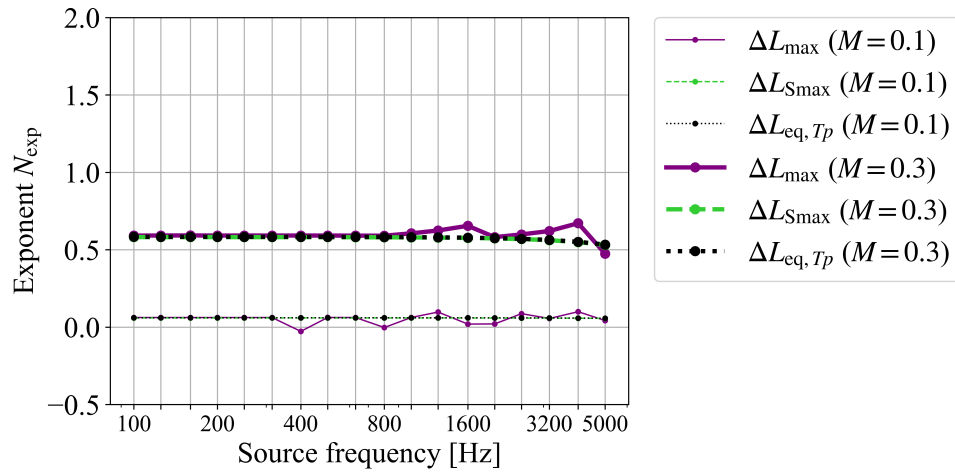
where $N_{\text{exp}}(M)$ is the exponent of the relative levels, which is derived as

$$N_{\text{exp}}(M) = \frac{\Delta L(M + \Delta M) - \Delta L(M - \Delta M)}{10 \lg \left(\frac{M + \Delta M}{M - \Delta M} \right)}.\quad (5.45)$$

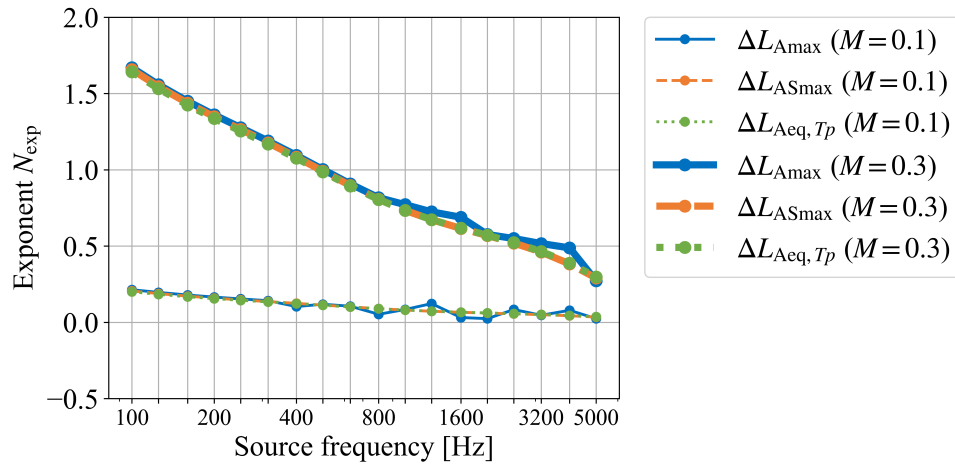
Figure 5.14 shows the computed exponents of relative SPLs and relative A-weighted SPLs for the same cases as the previous section. ΔM was set as 0.003 in the computations.

Figure 5.14(a) shows the exponents of the relative SPLs: ΔL_{max} , ΔL_{Smax} and $\Delta L_{\text{eq},Tp}$. In this figure, N_{exp} is approximately 0.05 at $M = 0.1$ and 0.6 at $M = 0.3$ for all the relative levels regardless of the source frequency. This reveals that the contribution of source movement results in larger differences in SPLs as source velocity increases while the level differences appear to be almost independent of source frequency.

On the other hand, Fig. 5.14(b) shows the exponents of the relative A-weighted SPLs: ΔL_{Amax} , ΔL_{ASmax} and $\Delta L_{\text{Aeq},Tp}$. This figure shows that N_{exp} at $M = 0.3$ is larger than that at $M = 0.1$ for all the source frequencies as well as Fig. 5.14(a). However, N_{exp} of all the A-weighted SPLs and both of the Mach numbers reach their maximum when the source frequency is 100 Hz, and they all monotonically decrease as the source frequency increases. When the source frequency is 100 Hz, N_{exp} is approximately 0.2 at $M = 0.1$ and 1.6 at $M = 0.3$ while it is approximately 0 at $M = 0.1$ and 0.3 at $M = 0.3$ when source frequency is 5000 Hz. This indicates that lower source frequencies result in a more rapid increase in A-weighted level differences as the source velocity increases. These results suggest that as the source velocity increases and source frequency decreases, the exponent also increases more significantly as well as the relative A-weighted SPLs themselves.



(a) Exponent N_{exp} of the relative SPLs ΔL_{max} , ΔL_{Smax} and $\Delta L_{\text{eq}, Tp}$



(b) Exponent N_{exp} of the relative A-weighted SPLs ΔL_{Amax} , ΔL_{ASmax} and $\Delta L_{\text{Aeq}, Tp}$

Figure 5.14: Exponent N_{exp} of the relative SPLs and the relative A-weighted SPLs.

5.6 Summary

Transportation noise source was simplified as a point source group moving along a straight track. Then the effects of frequency and amplitude modulation caused by the source movement were examined in terms of their impact on evaluation of noise metrics used in transportation noise prediction. The three noise metrics considering the modulation were calculated when the source group moves at a constant velocity on a straight track: maximum A-weighted SPL L_{Amax} , Maximum A-weighted SPL L_{ASmax} with time weighting S (slow), and A-weighted equivalent continuous sound pressure level $L_{Aeq,Tp}$ on the pass-by time. The results were compared with calculated levels without considering source movement. To examine the effects of them on propagation of radiated sound, the sound power was considered constant with respect to the source velocity. The results are summarized as the following.

1. When a sound source group moves, the frequency and amplitude increase when sound sources are approaching and decrease when going away as well as a single sound source.
2. Comparing the cases with and without considering frequency and amplitude modulation, all the calculated levels of noise metrics became larger than the levels without their consideration.
3. The difference of the calculated levels between the cases increased with respect to the sound source velocity and the difference of all the noise metrics reached approximately 1.2 dB at 300 km/h. However, this was independent of distance between the track and the receiver. Noise metrics may be underestimated compared to actual conditions without their consideration.
4. Approximating discrete sound sources in line by a finite line source would underestimate the noise metrics. The level of this underestimation would increase by decreasing source division and was large in order of $L_{Aeq,Tp}$, L_{ASmax} , and L_{Amax} .
5. The level differences with or without considering the modulation decrease monotonically with respect to source frequency due to A-weighting. When noise from the source group contains wideband frequency components, the low frequency component of this contribute more significantly to the increase in A-weighted SPL when the modulation is considered. If the source frequency is constant, the calculated

A-weighted SPLs increase as the source velocity increases.

They suggest that neglecting source movement may lead to underestimation of noise metrics in transportation noise prediction at higher source velocities and lower source frequencies.

Chapter 6

Conclusion

6.1 Summary

I numerically and experimentally investigated the changes of the directivities of sound sources due to source movement at low Mach number and clarified the differences in amplitude modulation caused by source movement depending on the type of source. Then I examined how frequency and amplitude modulation due to source movement affect the evaluation of noise metrics used in transportation noise prediction when a series of point sources moves along a straight trajectory.

In Chapter 2, frequency and amplitude modulation of a moving point source or a point source fixed in the air flow is introduced. For a moving point source, Doppler factor is defined as the ratio of frequency of radiated sound at a receiver to the pulsation frequency of the source. When a sound source is fixed in air flow, the ratio of apparent wavelength of radiated sound to the wavelength of the sound at the pulsation frequency of the source represents the expansion and contraction of the apparent wavelength as seen by an observer moving with the air flow and is reciprocal of Doppler factor when the source is moving in the stationary air. Therefore, the spatial expansion or contraction of the apparent wavelength of the radiated sound due to the Mach number of the sound source or the air flow is a phenomenon common to both source movement and convection. Because sound pressure or intensity of radiated sound in the farfield from moving point sources or sources fixed in the air flow are expressed as powers of the Doppler factor or the ratio, amplitude modulation of the radiated sound by source movement and that by convection can be compared using Doppler factor or the ratio.

In Chapter 3, a launching experiment was performed using a scaled train model with

an ultrasonic transducer as a simplified vibrational sound source and with an aerodynamic sound source radiating aeolian tone sound, which is a typical dipole component of aerodynamic sound. The measurements of directivities of these moving sources were conducted at various source velocities at low Mach numbers to derive motional amplitude modulations of radiated sound. Then how the two sound source types affect the amplitude modulation of radiated sound was discussed as a result of source movement. The experimental results revealed that the acoustic intensity of sound radiated from the vibrational sound source increases roughly in proportion to the fourth power of the Doppler factor, whereas that of the dipole component of aerodynamic sound increases roughly in proportion to the eighth power of the Doppler factor. They suggest that sound radiated from an aerodynamic source moving at low Mach numbers leads to a larger amplitude modulation due to source movement compared with sound radiated from a vibrational source, indicating the necessity of applying corrections for the sound source movement for each type of sound source in noise prediction models.

In Chapter 4, the influence of source movement or convection on the amplitude of radiated aerodynamic sound was investigated experimentally. The directivities of a simplified aerodynamic sound source were measured at a fixed position out the flow in a wind tunnel at various flow velocities at low Mach number. The source was radiating aeolian tone sound that was a dipole component of aerodynamic sound and was caused by pressure fluctuations. The results show that, because of convection, the acoustic intensity of radiated sound increases approximately in inverse proportion to the fourth power of the ratio of the apparent wavelength in the flow to the original wavelength. The amplitude modulations obtained by the wind tunnel measurements were compared with the modulation due to sound source movement. The results suggest that an aerodynamic sound yields a larger amplitude modulation because of source movement rather than convection when the apparent wavelength of radiated sound in the atmosphere changes by the same proportion. The finding suggests that the radiated sound pressure level of an aerodynamic sound estimated in wind tunnel experiments may be underestimated compared to the level of the same aerodynamic source which is actually moving in the air.

In Chapter 5, transportation noise source was simplified as a point source group moving along a straight track and the effect of sound source movement on the radiated sound characteristics were examined in terms of their impact on evaluation of noise metrics used in transportation noise prediction. The three noise metrics considering the modu-

lation were calculated when the source group moves at a constant velocity on a straight track: maximum A-weighted SPL $L_{A\max}$, Maximum A-weighted SPL $L_{AS\max}$ with time weighting S (slow), and A-weighted equivalent continuous sound pressure level $L_{Aeq,Tp}$ on the pass-by time. The results were compared with calculated levels without considering source movement. To examine the effects of them on propagation of radiated sound, the sound power was considered constant with respect to the source velocity. The results are summarized as the following.

1. When a sound source group moves, the frequency and amplitude increase when sound sources are approaching and decrease when going away as well as a single sound source.
2. Comparing the cases with and without considering frequency and amplitude modulation, all the calculated levels of noise metrics became larger than the levels without their consideration.
3. The difference of the calculated levels between the cases increased with respect to the sound source velocity and the difference of all the noise metrics reached approximately 1.2 dB at 300 km/h. However, this was independent of distance between the track and the receiver. Noise metrics may be underestimated compared to actual conditions without their consideration.
4. Approximating discrete sound sources in line by a finite line source would underestimate the noise metrics. The level of this underestimation would increase by decreasing source division and was large in order of $L_{Aeq,Tp}$, $L_{AS\max}$, and $L_{A\max}$.
5. The level differences with or without considering the modulation decrease monotonically with respect to source frequency due to A-weighting. When noise from the source group contains wideband frequency components, the low frequency component of this contribute more significantly to the increase in A-weighted SPL when the modulation is considered. If the source frequency is constant, the calculated A-weighted SPLs increase as the source velocity increases.

It is suggested from these results that neglecting source movement may lead to underestimation of noise metrics in transportation noise prediction at higher source velocities and lower source frequencies.

Finally, from the results of all the chapter in the entire dissertation, it can be concluded that ignoring frequency and amplitude modulation associated with sound source movement, as the existing noise prediction models, may underestimate the noise metrics used in the prediction models. The underestimation on noise metrics (the peak or mean value in energy of A-weighted sound pressure levels) becomes more significant for sources moving at higher velocity and especially it reaches approximately 1.2 dB at a speed of 300 km/h. Improving transportation noise prediction models more accurately by considering source movement requires considering its physical mechanism, the method for measuring or estimating directivity, and its frequency characteristic as well as source velocity.

6.2 Future prospects

This study in this dissertation is expected to revise existing transportation noise prediction models or frameworks by adding the formulae in acoustic propagation calculations to correct the effect of source movement. As a result, the following prospects are expected.

6.2.1 Compatibility with geographical features and surrounding environments

In Japan, the assessment of compliance with environmental standards for railway noise is still conducted solely through field measurements. Consequently, health risk assessments require noise measurements at each location where the environment around the vehicles and tracks changes, and a large number of measurements are required to understand the noise distribution throughout the cities.

By incorporating the findings of these studies into the estimation methods for sound source models and noise prediction models, it will be possible to model transportation noise from actual measurement data of vehicles while ensuring compatibility with geographical features and surrounding track or road environments. Simultaneously, these estimated models will enable highly accurate noise prediction under varying conditions, such as different vehicle types, operating speeds, and infrastructure environments. As a result, it will be feasible to compare noise distributions across different regions where the same vehicles operate, as well as to estimate temporal changes in noise distributions due to variations in vehicles, facilities, and geographical conditions.

6.2.2 Improved operating speeds of railway vehicles and compliance with environmental standards

Since railways emit less carbon dioxide than automobiles and aircraft, improving convenience through increased operating speeds will lead to reduced environmental impact. However, as train speeds increase, noise emissions generally rise, and there is a risk of violating environmental standards in various countries.

The more accurate noise modeling or estimation methods, as described in the previous section and based on the findings of these studies, will make it possible to predict the changes in noise emissions from various parts of the train as speed increases, which currently require measurements in field test. Such noise predictions can be used to estimate the required amount of noise reduction for each part of trains and the required performance of noise barriers at the design phase of railway vehicles, thereby facilitating the proactive implementation of effective noise reduction measures.

Furthermore, standardized methods for noise measurement emitted by railbound vehicles have been adopted in the Technical Specifications for Interoperability (TSI) [117] issued by the European Railway Agency (ERA) and ISO standards [114] for railway manufacturers. This estimation method will enable railway manufacturers to accurately predict railway noise under these standardized test conditions, facilitating verification of compliance with environmental standards across different countries.

6.2.3 Development of research on health risks caused by noise

The World Health Organization Regional Office for Europe provides recommended noise levels to various types of environmental noise to safeguard public health, while also evaluating the quality of the epidemiological surveys that support these recommendations [2]. According to this, for example, the accuracy of the surveys on railway noise is low, primarily due to the difficulty of accurately estimating the noise exposure of residents living along railway lines. However, measuring noise exposure in wide-ranging railway area would require enormous labor and costs.

The more accurate noise modeling or estimation described in Section 6.2.1 are expected to contribute to precise estimation of noise exposure for residents over large areas with significantly reduced labor requirements, not only for the present but also for the past and future. Combining the estimations with epidemiological surveys (cohort studies) of residents living along railway lines will enable a higher level of understanding of noise

exposure and its health impacts of the residents. It may thus contribute to the revision and implementation of environmental standards for transportation noise around the world based on higher quality scientific evidence.

6.3 Future issues

Firstly, in the experimental investigations in Chapters 3 and 4, linear regression was performed on the amplitude modulation due to the Doppler factor and source movement or convection, referring to the method of the preceding study by Norum *et al.* [77]. The standard deviation between the measured $\Delta L_{\text{Doppler}}$ or $\Delta L_{\text{conv.}}$ and the linear regression line of data acquired in both experiments were larger than 1.0 dB, which are larger than the corresponding standard deviation in the experimental study by Norum *et al.* [77]. This larger standard deviation might be attributable to the height difference between the source and the microphone Δz_{AE} not being sufficiently larger than the wavelength of aerodynamic sound. It is necessary to improve the measurement accuracy of the amplitude modulation of the radiated aerodynamic sound induced by sound source movement in a scaled train model experiment and by convection in a wind tunnel experiment.

Secondly, transportation noise sources in urban areas include vehicles moving at not only low Mach numbers but also higher Mach numbers such as aircraft. It is necessary to investigate how source movement or convection affects the amplitude modulation of radiated sound at higher Mach numbers by not only theoretical or numerical investigations but also experimental ones.

Thirdly, in Chapter 5, assuming the movement of a group of sound sources, the effect of frequency and amplitude modulation due to source movement on noise metrics was clarified. In this study, each sound source constituting the source group was an omnidirectional point source, and a source group was defined as a set of vibrational sources arranged at equal intervals. However, in modern high-speed railways, aerodynamic noise is dominant and is considered to have a significant contribution. As shown in Chapter 3, although the directivity and amplitude variations of aerodynamic sources due to source movement differ from those of vibrational sources, the effect of source movement on noise metrics for radiated aerodynamic sound has not yet been clarified. Therefore, in addition to the study conducted in Chapter 5, it is necessary to investigate cases where the source group consists of aerodynamic sources rather than vibrational sources.

Furthermore, structures such as elevated bridges and noise barriers exist in actual cities, causing diffraction and reflection of radiated sound during propagation. For instance, if an absorptive surface is present around the sound source, the absorption effect of the surface may change due to frequency modulation caused by the Doppler effect. In the case of a noise barrier, frequency modulation due to source movement may lead to changes in the sound insulation performance. If the noise barrier is equipped with an absorptive surface, the combined effect of absorption changes and frequency modulation may further alter the sound insulation performance. Investigating the impact of frequency and amplitude modulation due to source movement on the sound insulation performance of noise barriers under these conditions remains a future issue.

Bibliography

- [1] World Health Organization Regional Office for Europe, “Burden of disease from environmental noise: Quantification of healthy life years lost in Europe,” Copenhagen, 2011.
- [2] World Health Organization Regional Office for Europe, “Environmental Noise Guidelines for the European Region,” Copenhagen, 2018.
- [3] European Union, “Directive 2002/49/EC,” 2002.
- [4] The NOISE Observation & Information Service for Europe, European Environment Agency
<https://noise.eea.europa.eu/>, retrieved 2025-05-30.
- [5] National Transportation Noise Map
<https://maps.dot.gov/BTS/NationalTransportationNoiseMap/>, retrieved 2025-05-30.
- [6] National Transportation Noise Map — Bureau of Transportation Statistics
<https://www.bts.gov/newsroom/bts-releases-national-transportation-noise-map>,
 retrieved 2025-05-30.
- [7] END LAB.
<https://end-lab.jp/noise-map/index.html>, retrieved 2025-05-30 (in Japanese).
- [8] J. Defrance, E. Salomons, I. Noordhoek, D. Heimann, B. Plovsing, G. Watts, H. Jonasson, X. Zhang, E. Premat, I. Schmich, F. Aballea, M. Baulac and F. D. Roo, “Outdoor sound propagation reference model developed in the European Harmonoise project,” *ACUSTICA*, 93, pp.213-227, 2007.

- [9] S. Kephelopoulos, M. Paviotti and F. Anfosso-Lédée, "Common noise assessment methods in Europe (CNOSSOS-EU)," *JRC reference reports*, EUR 25379 EN, pp.1-180, 2012.
<https://doi.org/10.2788/32029>
- [10] Y. Okada, K. Anai, T. Itiki, K. Yamauchi, Y. Yasuda, and T. Yokota, "Road traffic noise prediction model "ASJ RTN-Model 2023": Report of the Research Committee on Road Traffic Noise," *Acoust. Sci. & Tech.*, **46**(4), pp.365-429, 2025.
<https://doi.org/10.1250/ast.e24.125>
- [11] Y. Moritoh, K. Nagakura, H. Tachikawa, and S. Ogata, "Proposal of a prediction model for noise of conventional railway," *The Journal of the INCE of Japan*, **20**(3), pp.32-37, 1996.
<https://doi.org/10.11372/souonseigyo1977.20.146>
- [12] K. Nagakura and Y. Zenda, "Prediction model of wayside noise level of Shinkansen," *RTRI Report*, **14**(9), pp.5-10, 2000 (in Japanese).
- [13] J. Billingsley and R. Kinns, "The acoustic telescope," *J. Sound Vib.*, **48**(4), pp.485-510, 1976.
[https://doi.org/10.1016/0022-460X\(76\)90552-6](https://doi.org/10.1016/0022-460X(76)90552-6)
- [14] S. Guérin and C. Weckmüller, "Frequency-domain reconstruction of the point-spread function for moving sources," *Proc. BeBeC 2008*, BeBeC-2008-14, 2008.
- [15] G. P. Howell, A. J. Bradley, M. A. McCormick, and J. D. Brown, "De-dopplerization and acoustic imaging of aircraft flyover noise measurement," *J. Sound Vib.*, **195**(1), pp.151-167, 1986.
[https://doi.org/10.1016/0022-460X\(86\)90227-0](https://doi.org/10.1016/0022-460X(86)90227-0)
- [16] B. Barsikow, W. F. King III, and E. Pfizenmaier, "Wheel/rail noise generated by a high-speed train investigated with a line array of microphones," *J. Sound Vib.*, **118**(1), pp.99-122, 1987.
[https://doi.org/10.1016/0022-460X\(87\)90257-4](https://doi.org/10.1016/0022-460X(87)90257-4)
- [17] B. Barsikow and W.F. King III, "On removing the Doppler frequency shift from array measurements of railway noise," *J. Sound Vib.*, **120**(1), pp.190-196, 1988.
[https://doi.org/10.1016/0022-460X\(88\)90344-6](https://doi.org/10.1016/0022-460X(88)90344-6)

- [18] J. J. Kelly and M. R. Wilson, “De-dopplerization of aircraft acoustic signals,” *J. Aircraft*, **32**(5), pp.1012-1017, 1995.
<https://doi.org/10.2514/3.46830>
- [19] J. F. Piet, G. Elias, and P. Lebigot, “Localization of acoustic source from a landing aircraft with a microphone array,” *Proc. 11th AIAA/CEAS Aeroacoustics Conference and Exhibit*, AIAA-99-1811, Bellevue, WA, 1999.
<https://doi.org/10.2514/6.1999-1811>
- [20] L. Brusniak, J. R. Underbrink, and R. W. Stoker, “Acoustic imaging of aircraft noise sources using large aperture phased arrays,” *Proc. 11th AIAA/CEAS Aeroacoustics Conference*, AIAA-2006-2715, Cambridge, Massachusetts, 2006.
<https://doi.org/10.2514/6.2006-2715>
- [21] Y. Takano, K. Terada, E. Aizawa, A. Iida, and H. Fujita, “Development of a 2-dimensional microphone array measurement system for noise sources of fast moving vehicles,” *Proc. Inter-Noise 1992*, Toronto, Canada, pp.1175–1178, 1992.
- [22] Y. Takano, “X-shaped two-dimensional microphone array system for measuring noise-source distribution on moving vehicles,” *JSME International Journal Series C*, **41**(1), pp.46-50, 1998.
- [23] S. Brühl, K. P. Schmitz, “Noise source localization on highspeed trains using different array types,” *Proc. Inter-Noise 1993*, Leuven, Belgium, pp.1311–1314, 1993.
- [24] B. Barsikow, “Experiences with various configurations of microphone arrays used to locate sound sources on railway trains operated by the DB AG,” *J. Sound Vib.*, **193**(1), pp.283–293, 1996.
<https://doi.org/10.1006/jsvi.1996.0269>
- [25] J. A. Högbom, “Aperture synthesis with a non-regular distribution of interferometer baselines,” *Astron. Astrophys. Suppl.*, **15**, pp.417-426, 1974.
- [26] T. F. Brooks and W. M. Humphreys, “A deconvolution approach for the mapping of acoustic sources (DAMAS) determined from phased microphone arrays,” *J. Sound Vib.*, **294**(4-5), pp.856–879, 2006.
<https://doi.org/10.1016/j.jsv.2005.12.046>

- [27] R. P. Dougherty, “Extensions of DAMAS and benefits and limitations of deconvolution in beamforming,” *Proc. 11th AIAA/CEAS Aeroacoustics Conference*, AIAA-2005-2961, Montrey, CA, 2005.
<https://doi.org/10.2514/6.2005-2961>
- [28] T. F. Brooks and W. M. Humphreys, “Extension of DAMAS phased array processing for spatial coherence determination (DAMAS-C),” *Proc. 12th AIAA/CEAS Aeroacoustics Conference*, AIAA-2006-2654, Cambridge, Massachusetts, 2006.
<https://doi.org/10.2514/6.2006-2654>
- [29] P. Sijtsma, “CLEAN based on spatial source coherence,” *Int. J. Aeroacoust.*, **6**(4) pp.357–374, 2007.
<https://doi.org/10.1260/147547207783359459>
- [30] R. Cousson, Q. Leclerc, M. Pallas and M. Berengier, “A time domain CLEAN approach for the identification of acoustic moving sources. Journal of Sound and Vibration,” *J. Sound Vib.*, **443**, pp.47-62, 2019.
<https://doi.org/10.1016/j.jsv.2018.11.026>
- [31] T. Yardibi, J. Li, P. Stoica, and L. N. Cattafesta III, “Sparsity constrained deconvolution approaches for acoustic source mapping,” *J. Acoust. Soc. Am.*, **123**(5) pp.2631–2642, 2008.
<https://doi.org/10.1121/1.2896754>
- [32] Z. Chu and Y. Yang, “Comparison of deconvolution methods for the visualization of acoustic sources based on cross-spectral imaging function beamforming,” *Mech. Syst. Signal Process.*, **48**(1–2) pp.404–422., 2014.
<https://doi.org/10.1016/j.ymssp.2014.03.012>
- [33] S. Guérin, C. Weckmüller, and U. Michel, “Beamforming and deconvolution for aerodynamic sound sources in motion,” *Proc. BeBeC 2006*, BeBeC-2006-16, 2006.
- [34] S. Guérin and H. Siller, “A hybrid time-frequency approach for the noise localization analysis of aircraft fly-overs,” *Proc. 14th AIAA/CEAS Aeroacoustics Conference*, AIAA-2008-2955, Vancouver, British Columbia, Canada, 2008.
<https://doi.org/10.2514/6.2008-2955>

- [35] J. Hald, Y. Ishii, T. Ishii, H. Oinuma, K. Nagai, Y. Yokokawa, and K. Yamamoto, "High-resolution fly-over Beamforming using a small practical array," *Proc. 18th AIAA/CEAS Aeroacoustics Conference*, AIAA-2012-2229, Colorado Springs, CO, 2012.
<https://doi.org/10.2514/6.2012-2229>
- [36] V. Fleury, J. Bulté, "Extension of deconvolution algorithms for the mapping of moving acoustic sources," *J. Acoust. Soc. Am.*, **129**(3), pp.1417–1428, 2011.
<https://doi.org/10.1121/1.3531939>
- [37] V. Fleury, P. Malbécui, "Slat noise assessment from Airbus A340 flyover phased-array microphone measurements," *AIAA J.*, **51**(7), pp.1667–1674, 2013.
<https://doi.org/10.2514/1.J052054>
- [38] T. Takaishi, T. Kobayashi, Y. Ikuta, and Taro Imamura, "Component-wise regression sound source models for the aircraft noise prediction framework J-FRAIN," *Proc. Inter-Noise 2023*, pp.690–701, Chiba, Japan, 2023.
https://doi.org/10.3397/IN_2023_0112
- [39] T. Kobayashi, T. Yokota, K. Makino, Y. Ikuta, T. Imamura, T. Takaishi, and Y. Kawase, "Verification and application of the aircraft noise simulation framework J-FRAIN," *Proc. Inter-Noise 2023*, pp.702–713, Chiba, Japan, 2023.
https://doi.org/10.3397/IN_2023_0113
- [40] T. Nakazawa, N. Shinohara, M. Sugawara, K. Hanaka, T. Kobayashi, and R. Yamamoto, "Study on noise calculation method considering gear and flap conditions during aircraft landing," *Proc. Inter-Noise 2023*, pp.3070–3076, Chiba, Japan, 2023.
https://doi.org/10.3397/IN_2023_0445
- [41] S. E. Wright, "Sources and observers in motion, I: time variant analysis and its implications for aerodynamic sound," *J. Sound Vib.*, **108**(3), pp.361–378, 1986.
[https://doi.org/10.1016/S0022-460X\(86\)80033-5](https://doi.org/10.1016/S0022-460X(86)80033-5)
- [42] S. Ogata, H. Tsuru, H. Nakajima, and K. Fujiwara, "Investigation for insertion loss of noise barrier for sound source moving at high speed," *Acoust. Sci. & Tech.*, **24**(3), pp.148–150, 2003.
<https://doi.org/10.1250/ast.24.148>

- [43] M. Akutsu, T. Uda, K. Yatabe, and Y. Oikawa, "Visualization of sound wave from high-speed moving source," *Acoust. Sci. & Tech.*, **43**(6), pp.339–341, 2022.
<https://doi.org/10.1250/ast.43.339>
- [44] M. Akutsu, T. Uda, K. Yatabe, and Y. Oikawa, "Experimental observation of the sound field around a moving source using parallel phase-shifting interferometry," *Proc. Inter-Noise 2022*, pp.3733–3739, Glasgow, Scotland, 2022.
https://doi.org/10.3397/IN_2022_0525
- [45] M. Akutsu, T. Uda, and Y. Oikawa, "Experimental evaluation of characteristics for high-speed moving source," *Proc. Inter-Noise 2023*, pp.4830–4837, Chiba, Japan, 2023.
https://doi.org/10.3397/IN_2023_0686
- [46] M. Akutsu, T. Uda, K. Yatabe, and Y. Oikawa, "Visualization of sound waves around high-speed moving source using parallel phase-shifting interferometry," *Proc. ICA 2022*, ABS-0277, Gyeongju, Korea, 2022.
- [47] M. Akutsu, T. Uda, and Y. Oikawa, "Experimental and quantitative evaluation of frequency modulation caused by Doppler effect around high-speed moving sound source," *J. Acoust. Soc. Am.*, **154**(5), pp.3403–3413, 2023.
<https://doi.org/10.1121/10.0022537>
- [48] M. Akutsu, T. Uda, and Y. Oikawa, "Sound wave propagation in the boundary layer around moving source," *Acoust. Sci. & Tech.*, **46**(4), pp.453–462, 2025.
<https://doi.org/10.1250/ast.e24.71>
- [49] e.g., JSME, *JSME Mechanical Engineers' Handbook, Series α , $\alpha 4$: Fluids Engineering*, JSME, Tokyo, 2006 (in Japanese).
- [50] P. M. Morse and K. U. Ingard, *Theoretical Acoustics*, McGraw-Hill, New York, 1968.
- [51] M. S. Howe, *Acoustics of Fluid-Structure Interactions*, Cambridge University Press, Cambridge, 1998.
- [52] J. Zhang, G. Squicciarini, and D. J. Thompson, "Implications of the directivity of railway noise sources for their quantification using conventional beamforming," *J.*

- Sound Vib.*, **459**(114841), 2019.
<https://doi.org/10.1016/j.jsv.2019.07.007>
- [53] A. Kujawski and E. Sarradj, “Application of the CLEAN method for high speed railway train measurements,” *Proc. BeBeC 2020*, BeBeC-2020-D2, 2020.
- [54] R. Leiba, Q. Leclère and E. Julliard, “Application of the CLEAN methodology to flyover noise measurements,” *Proc. BeBeC 2022*, BeBeC-2022-D06, 2022.
- [55] F. Meng, B. Masiero, and M. Vorländer, “Compressive beamforming for moving sound source auralization,” *Proc. Inter-noise 2016*, Hamburg, Germany, pp.4556-4561, 2016.
- [56] F. Meng, G. Behler, and M. Vorländer, “A synthesis model for a moving sound source based on beamforming,” *Acta Acust united Ac*, **104**(2), pp.351–362, 2018.
<https://doi.org/10.3813/AAA.919177>
- [57] F. Meng, Y. Li, B. Masiero, and M. Vorländer, “Signal reconstruction of fast moving sound sources using compressive beamforming,” *Appl. Acoust.*, **150**, pp.236–245, 2019.
<https://doi.org/10.1016/j.apacoust.2019.02.012>
- [58] R. Cousson, M. Pallas, Q. Leclère, and M. Bérengier, “Identification of acoustic moving sources in the context of a road vehicle at pass-by,” *Proc. Mtgs. Acoust.*, **30**, 040012, 2017.
<https://doi.org/10.1121/2.0000645>
- [59] H. Kook, G. B. Moebs, P. Davies and J. S. Bolton, “An efficient procedure for visualizing the sound field radiated by vehicles during standardized passby tests,” *J. Sound Vib.*, **233**(1), pp.137–156, 2000.
<https://doi.org/10.1006/jsvi.1999.2794>
- [60] C. Long and C. Y. Sze, “Fault identification and localization for moving wheels based on de-Dopplerization beamforming kurtosis method,” *Proc. BeBeC 2018*, BeBeC-2018-D18, 2018.

- [61] H. M. Noh and J. W. Choi, "Identification of low frequency noise sources in high-speed train via resolution improvement," *J. Mech. Sci. & Tech.*, **29**(9), pp.3609-3615, 2015.
<https://doi.org/10.1007/s12206-015-0804-8>
- [62] G. Zechel, A. Zeibig, and M. Beitel Schmidt, "Time domain beamforming on moving objects with known trajectories," *Proc. BeBeC 2010*, BeBeC-2010-12, 2010.
- [63] W. T. Mo and S. M. Yung, "Power estimation of sound sources on low-speed electric trains using a deconvolution approach," *J. Acoust. Soc. Am.*, **105**(4), pp.2350-2358, 1999.
<https://doi.org/10.1121/1.426858>
- [64] F. Miao, D. Yang, J. Wen, and X. Lian, "Moving sound source localization based on triangulation method," *J. Sound Vib.*, **385**(7), pp.93-103, 2016.
<http://dx.doi.org/10.1016/j.jsv.2016.09.001>
- [65] C. Camier, J. F. Blais, R. Lapointe, and A. Berry, "A time-domain analysis of 3D non-uniform moving acoustic sources: application to source identification and absolute quantification via beamforming," *Proc. BeBeC 2012*, BeBeC-2012-30, 2012.
- [66] D. Dragna, P. Blanc-Benon and F. Poisson, "Modeling of broadband moving sources for time-domain simulations of outdoor sound propagation," *AIAA J.*, **52**(9), pp.1928-1939, 2014.
<https://doi.org/10.2514/1.J052672>
- [67] D. Dragna, P. Blanc-Benon, E. Bongini, and F. Poisson, "Outdoor sound propagation for high-speed moving sources," *Proc. Mtgs. Acoust.*, **19**, 040144, 2013.
<https://doi.org/10.1121/1.4800004>
- [68] A. Dowling, "Convective amplification of real simple sources," *J. Fluid Mech.*, **74**(8), pp.529-546, 1976.
<https://doi.org/10.1017/S0022112076001936>
- [69] M. J. Lighthill, "On sound generated aerodynamically: I. General theory," *Proc. Royal Soc. London Series A*, **211**(1107), pp.564-587, 1952.
<https://doi.org/10.1098/rspa.1952.0060>

- [70] Y. Makino and Y. Takano, "Basic study on radiation sound characteristics of sound sources moving at the same speed," *Tech. Rep. Noise and Vib. Acoust. Soc. Jpn.*, N2020-09, 2020 (in Japanese).
- [71] Y. Makino and Y. Takano, "The influence of frequency and amplitude modulation due to the sound source movement on radiated sound characteristics," *Trans. Jpn. Soc. Mech. Eng.*, **87**(899), 21-00052, 2021 (in Japanese).
<https://doi.org/10.1299/transjsme.21-00052>
- [72] Y. Makino and Y. Takano, "Effect of sound source movement at low Mach number on radiated noise level," *Proc. Inter-Noise 2021*, pp.3731-3737, Washington, D.C., USA, 2021.
<https://doi.org/10.3397/IN-2021-2503>
- [73] G. C. Gaunaurd and L. H. Nguyen, "Acoustic power radiated from the uniform motion of a source of finite size," *ACUSTICA*, **100**, pp.5–12, 2014.
<https://doi.org/10.3813/AAA.918681>
- [74] Y. Makino and Y. Takano, "Sound source directivity considering source movement," *Proc. Inter-Noise 2022*, pp.3579-3589, Glasgow, Scotland, 2022.
https://doi.org/10.3397/IN_2022_0505
- [75] S. Hoshika, K. Iwanaga, T. Doi, Y. Nakajima, and T. Ohshima, "An experiment of moving sound source with the launching train model system," *Proc. Autumn Meet. INCE/J*, pp.105-106, 2019 (in Japanese).
- [76] T. Doi, T. Ogawa, T. Masubuchi, and J. Kaku, "Development of an experimental facility for measuring pressure waves generated by high-speed trains," *J. Wind Eng. Ind. Aerodyn.* **98**, pp.55–61, 2010.
<https://doi.org/10.1016/j.jweia.2009.09.002>
- [77] T. D. Norum, D. P. Garber, R. A. Golub, O. L. Santa Maria, and J. S. Orme, "Supersonic jet exhaust noise at high subsonic flight speed," *NASA/TP-2004-212686*, 2004.
- [78] Y. Makino, Y. Takano, M. Akutsu, and T. Uda, "Measurement of radiated sound directivity of moving sources at low Mach numbers," *Proc. Inter-Noise 2023*, pp.1640-

- 1648, Chiba, Japan, 2023.
https://doi.org/10.3397/IN_2023_0247
- [79] Y. Makino, Y. Takano, M. Akutsu, and T. Uda, "Sound directivity measurement of aeolian tone of moving and stationary sound sources," *Proc. Intn'l. Workshop Env. Eng. 2023 (IWE 2023)*, E107, Shimane, Japan, 2023.
- [80] Y. Makino, Y. Takano, M. Otani, M. Akutsu, and T. Uda, "Experimental study on amplitude modulation of radiated sound due to movement of aerodynamic sound source," *Tech. Rep. Noise and Vib. Acoust. Soc. Jpn.*, N2024-13 (2024) (in Japanese).
- [81] Y. Makino, Y. Takano, M. Otani, M. Akutsu, and T. Uda, "Measured amplitude modulation of radiated sound from vibrational and aerodynamic sound sources moving at low Mach number," *Acoust. Sci. & Tech.*, **46**(4), pp.470-479, 2025.
<https://doi.org/10.1250/ast.e24.78>
- [82] U. Fey, M. König, and H. Eckelmann, "A new Strouhal-Reynolds-number relationship for the circular cylinder in the range $47 < Re < 2 \times 10^5$," *Phys. Fluids*, **10**(7), pp.1547-1549, 1998.
<https://doi.org/10.1063/1.869675>
- [83] U.S. Standard Atmosphere, *NOAA-S/T 76-1562*, U.S. Government Printing Office, Washington, D.C., 1976.
- [84] T. Miyachi, "Low-noise moving model test facility completed at RTRI," *Ascent*, **9**, p.22, 2021.
- [85] K. Nagakura, "Localization of aerodynamic noise sources of Shinkansen trains," *J. Sound Vib.*, **293**, pp.547-556, 2006.
<https://doi.org/10.1016/j.jsv.2005.08.043>
- [86] ISO 9613-1:1993, Acoustics - Attenuation of sound during propagation outdoors Part 1: Calculation of the absorption of sound by the atmosphere.
- [87] X. Zhang, "The directivity of railway noise at different speeds," *J. Sound Vib.*, **329**(25), pp.5273-5288, 2010.
<https://doi.org/10.1016/j.jsv.2010.07.003>

- [88] Y. H. Kim and J. W. Choi, *Sound Visualization and Manipulation*, John Wiley & Sons, Singapore, 2013.
- [89] T. J. Mueller, *Aeroacoustic Measurements*, in: *Experimental Fluid Mechanics*, first ed., Springer-Verlag, Berlin Heidelberg, 2002.
- [90] R. Tanigawa, K. Yatabe, and Y. Oikawa, "Experimental visualization of aerodynamic sound sources using parallel phase shifting interferometry," *Exp. Fluids*, **61**(206), 2020.
<https://doi.org/10.1007/s00348-020-03038-x>
- [91] Y. Makino, Y. Takano, M. Otani, M. Akutsu, and T. Uda, "Influence of sound source movement and convection on measured aeolian tone sound at low Mach number," *Acoust. Sci. & Tech.*, **46**(4), pp.315-325, 2025.
<https://doi.org/10.1250/ast.e24.121>
- [92] R. K. Amiet, "Refraction of sound by a shear layer," *J. Sound Vib.*, **58**(4), pp.467-482, 1978.
[https://doi.org/10.1016/0022-460X\(78\)90353-X](https://doi.org/10.1016/0022-460X(78)90353-X)
- [93] T. Doi, M. Hiroe, and J. Kaku, "A study on the measurement of sound radiated from a high-speed moving source," *Proc. Spring Meet. Acoust. Soc. Jpn.*, pp.739-740, 1997 (in Japanese).
- [94] H. Tsuru, H. Nakajima, and K. Takahashi, "Numerical simulation and auralization of moving sound source," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, pp.667-668, 2000 (in Japanese).
- [95] M. Buret, "New analytical models for outdoor moving sources of sound," *Ph.D. Thesis, Acoustics Research Group, Department of Environmental and Mechanical Engineering*, The Open University (U.K.), 2002.
- [96] D. Duhamel, "Efficient calculation of the three-dimensional sound pressure field around a noise barrier," *J. Sound Vib.*, **197**(5), pp. 547-571, 1996.
<https://doi.org/10.1006/jsvi.1996.0548>
- [97] S. N. Chandler-Wilde, "Tyndall Medal lecture: the boundary element method in outdoor noise propagation," *Proc. Inst. Acoust.*, **19**(8), pp.27-50, 1997.

- [98] P. Jean, "A variational approach for the study of outdoor sound propagation and application to railway noise," *J. Sound Vib.*, **212**(2), pp.275-294, 1998.
<https://doi.org/10.1006/jsvi.1997.1407>
- [99] S. Sakamoto, "Calculation of sound propagation in three-dimensional field with constant cross section by Duhamel's efficient method using transient solutions obtained by finite-difference time-domain method," *Acoust. Sci. & Tech.*, **30**(2), pp.72-82, 2009.
<https://doi.org/10.1250/ast.30.72>
- [100] S. Ogata, H. Tsuru, H. Nakajima, and K. Fujiwara, "Investigation on insertion loss of noise barrier for high-speed moving sound source," *J. Acoust. Soc. Jpn.*, **59**(12), pp.713-722, 2003 (in Japanese).
https://doi.org/10.20697/jasj.59.12_713
- [101] H. Nakajima, H. Tsuru, and S. Ogata, "Analysis and error investigation using Fourier transform of sound field produced by moving source," *J. Acoust. Soc. Jpn.*, **60**(12), pp.717-726, 2004 (in Japanese).
https://doi.org/10.20697/jasj.60.12_717
- [102] C. H. Kasess and H. Waubke, "Moving sources and the 2.5D Helmholtz boundary element method," *Proc. ICA 2019*, pp.7475-7482, 2019.
<https://doi.org/10.18154/RWTH-CONV-239369>
- [103] E. J. Rathe, "Railway noise propagation," *J. Sound Vib.*, **51**(3), pp.371-388, 1977.
[https://doi.org/10.1016/S0022-460X\(77\)80079-5](https://doi.org/10.1016/S0022-460X(77)80079-5)
- [104] R. Makarewicz, J. Jarzęcki, K. Berezowska-Apolinarska and A. Preis, "Rail transportation noise with and without a barrier," *Appl. Acoust.*, **26**, pp.135-147, 1989.
[https://doi.org/10.1016/0003-682X\(89\)90067-4](https://doi.org/10.1016/0003-682X(89)90067-4)
- [105] Y. Okumura and K. Kuno, "Multiple regression analysis of railway noise based on finite line source models including the excess attenuation," *J. Acoust. Soc. Jpn. (E)*, **13**(3), pp.161-169, 1992.
<https://doi.org/10.1250/ast.13.161>

- [106] Y. Y. Lee, J. C. Kim and H. S. Lee, "A study to estimate the emitted sound power from the rolling stock," *JKSR*, **14**(3), pp.211-215, 2011.
<https://doi.org/10.7782/JKSR.2011.14.3.211>
- [107] K. Ishii, M. Koyasu, Y. Cho and H. Koba, "Draft proposal of the prediction of noise from elevated railway," *The Journal of the INCE of Japan*, **4**(2), pp.4-10, 1980.
<https://doi.org/10.11372/souonseigyo1977.4.64>
- [108] Y. Abe, K. Nagakura and T. Kitagawa, "Study on the prediction technique of conventional railway noise," *Tech. Rep. Noise and Vib. Acoust. Soc. Jpn.*, N-2005-1, 2005.
- [109] T. Kobayashi, S. Yokoyama, H. Yano, H. Tachibana, "Modeling of sound sources for conventional railway noise," *J. Acoust. Soc. Jpn.*, **66**(6), pp.257-264, 2010 (in Japanese).
https://doi.org/10.20697/jasj.66.6_257
- [110] L. A. M. van der Heijden and R. J. J. H. van Son, "A note on the neglect of the Doppler effect in the modelling of traffic flow as a line of stationary point sources," *J. Sound Vib.*, **85**(3), pp.442-444, 1982.
[https://doi.org/10.1016/0022-460X\(82\)90271-1](https://doi.org/10.1016/0022-460X(82)90271-1)
- [111] I. M. Ryzhik and I. S. Gradshteyn, *Table of integrals, series and products*, Academic Press, 1980.
- [112] IEC 61672-1:2013, Electroacoustics - Sound level meters - Part 1: Specifications, 2013.
- [113] BS EN 16272-3-1:2012, Railway applications - Track - Noise barriers and related devices acting on airborne sound propagation - Test method for determining the acoustic performance - Part 3-1: Normalized railway noise spectrum and single number ratings for diffuse field applications, 2012.
- [114] ISO 3095:2013, Acoustics - Railway applications - Measurement of noise emitted by railbound vehicles.

- [115] Environmental Quality Standards for Shinkansen Superexpress Railway Noise — Air & Transportation — Ministry of the Environment, Government of Japan
<https://www.env.go.jp/en/air/noise/railway.html>, retrieved 2025-06-13.
- [116] Chap. 4 Noise, Compendium of Reference Materials on the Basis for Establishment of Environmental Quality Standards in Japan, National Institute for Environmental Studies, Japan
<https://www.nies.go.jp/eqsbasis/en/noise.html>, retrieved 2025-06-13.
- [117] European Union, Regulation No 1304/2014 on the technical specification for interoperability relating to the subsystem ‘rolling stock — noise’ amending Decision 2008/232/EC and repealing Decision 2011/229/EU.

List of Publications

Journal articles

1. **Yusuke Makino** and Yasushi Takano, The influence of frequency and amplitude modulation due to the sound source movement on radiated sound characteristics, *Transactions of the JSME (in Japanese)*, Vol.87, No.899, 2021.
<https://doi.org/10.1299/transjsme.21-00052>
2. **Yusuke Makino**, Yasushi Takano, Makoto Otani, Mariko Akutsu, and Toki Uda, Influence of sound source movement and convection on measured aeolian tone sound at low Mach number, *Acoustical Science and Technology*, Vol.46, No.4, pp.315-325, 2025.
<https://doi.org/10.1250/ast.e24.121>
3. **Yusuke Makino**, Yasushi Takano, Makoto Otani, Mariko Akutsu, and Toki Uda, Measured amplitude modulation of radiated sound from vibrational and aerodynamic sound sources moving at low Mach number, *Acoustical Science and Technology*, Vol.46, No.4, pp.470-479, 2025.
<https://doi.org/10.1250/ast.e24.78>

Co-authored journal article

1. Takao Tsuchiya, **Yusuke Makino**, Yu Teshima, Shizuko Hiryu, Two-Dimensional Finite-Difference Time-Domain Simulation of Moving Sound Source and Receiver with Directivity, *Acoustical Science and Technology*, Vol.44, No.2, pp.101-109, 2023.
<https://doi.org/10.1250/ast.44.101>

International conference (Peer-reviewed)

1. **Yusuke Makino** and Yasushi Takano, Effect of sound source movement at low Mach number on radiated noise level, 50th International Congress and Exposition

on Noise Control Engineering (Inter-noise 2021), Online, August 2021.

2. **Yusuke Makino** and Yasushi Takano, Sound source directivity considering source movement, 51th International Congress and Exposition on Noise Control Engineering (Inter-noise 2022), Glasgow, UK, August 2022.
3. **Yusuke Makino**, Yasushi Takano, Mariko Akutsu, and Toki Uda, Measurement of radiated sound directivity of moving sources at low Mach numbers, 52nd International Congress and Exposition on Noise Control Engineering (Inter-noise 2023), Chiba, Japan, August 2023.

International conference (not peer-reviewed)

1. **Yusuke Makino**, Yasushi Takano, Mariko Akutsu, and Toki Uda, Sound directivity measurement of aeolian tone of moving and stationary sound sources, International Workshop on Environmental Engineering 2023 (IWEE 2023), Shimane, Japan, July 2023.
2. Yasushi Takano, Ryouhei Hanayama, and **Yusuke Makino**, Reverberation Analysis of Rectangular Room by Modal Synthesis Method, 52nd International Congress and Exposition on Noise Control Engineering (Inter-noise 2023), Chiba, Japan, August 2023.

Other conference proceedings and presentations (in Japanese)

1. **Yusuke Makino** and Yasushi Takano, Theoretical examination of acoustic propagation in a rectangular duct using image method, 2019 Autumn Meeting, Acoustical Society of Japan, 2-8-3, Sep 5, 2019.
2. **Yusuke Makino** and Yasushi Takano, Theoretical examination of acoustic propagation in a rectangular duct using image method, Technical Report of Noise and Vibration, Acoustical Society of Japan, N-2019-40, 2019.
3. **Yusuke Makino** and Yasushi Takano, Basic study on radiation sound characteristics of sound sources moving at the same speed, Technical Report of Noise and Vibration, Acoustical Society of Japan, N-2020-09, 2020.
4. **Yusuke Makino** and Yasushi Takano, Characteristics changes of the noise propagation from the sound source group movement, 2021 Spring Meeting, Acoustical

Society of Japan, 1-6-9, Mar 10, 2021.

5. **Yusuke Makino** and Yasushi Takano, Effect of sound source movement on radiated noise level, Proceedings of the Symposium on Environmental Engineering, 131, 2021.
6. **Yusuke Makino** and Yasushi Takano, Basic study on source modeling method for traffic noise considering the difference in acoustic propagation characteristics between static source and moving source, Technical Report of Noise and Vibration, Acoustical Society of Japan, N-2022-08, 2022.
7. **Yusuke Makino** and Yasushi Takano, Comparison between Japanese and European high-speed railway noise prediction models, 2022 Spring Meeting, Acoustical Society of Japan, 3-6-4, Mar 11, 2022.
8. **Yusuke Makino** and Yasushi Takano, Examination of accuracy of mathematical models that represent moving source, 2022 Spring Meeting, Acoustical Society of Japan, 3-6-10, Mar 11, 2022.
9. **Yusuke Makino**, Yasushi Takano, Mariko Akutsu, and Toki Uda, Experimental study on the effect of sound source movement on the directivity of radiated sound, 2022 Autumn Meeting, Acoustical Society of Japan, 2-Q-20, Sep 15, 2022.
10. **Yusuke Makino** and Yasushi Takano, Separation of stationary and moving sources at a constant velocity using a hybrid deconvolution approach, Technical Report of Noise and Vibration, Acoustical Society of Japan, N-2022-44(AA-2022-36), 2022.
11. **Yusuke Makino**, Yasushi Takano, Makoto Otani, Mariko Akutsu, and Toki Uda, Experimental study on the effect of sound source type on amplitude modulation of radiated sound due to source movement, 2023 Autumn Meeting, Acoustical Society of Japan, 1-7-10, Sep 26, 2023.
12. **Yusuke Makino**, Makoto Otani, and Yasushi Takano, A basic study on amplitude modulation of vibrating sound source due to sound source movement using spatial Fourier transform and plane wave synthesis, 2023 Autumn Meeting, Acoustical Society of Japan, 3-7-12, Sep 28, 2023.
13. **Yusuke Makino**, Yasushi Takano, Makoto Otani, Mariko Akutsu, and Toki Uda, Experimental study on amplitude modulation of radiated sound due to movement

of aerodynamic sound source, Technical Report of Noise and Vibration, Acoustical Society of Japan, N-2024-13, 2024.

Others

1. **Yusuke Makino**, Transportation noise prediction in cities, *Kyoto University Architectural Journal (traverse 22)*, 2022. (in Japanese)

Appendix A

Corrected sound pressure for the refraction of a shear layer

At first, assuming that a shear layer is planar and that the thickness of the shear layer is sufficiently small compared with the wavelength of the sound radiated from a sound source, the amplitude correction where the source is at the boundary between the potential core and the shear layer ($h = 0$) is represented as [92]

$$\begin{aligned} \left| \frac{p_{\text{c0p}}(h = 0)}{p_{\text{mic}}} \right| &= \frac{1 - M_{\text{flow}} \cos \theta'}{2} \\ &\times \left[\left(\frac{\zeta}{\sin \theta'} \right) + (1 - M_{\text{flow}} \cos \theta')^2 \right] \\ &= \frac{(1 + M_{\text{flow}} \cos \theta_r)^2 + \mu}{2 (1 + M_{\text{flow}} \cos \theta_r)^3 \mu}, \end{aligned} \quad (\text{A.1})$$

where p_{c0p} [Pa] is the corrected sound pressure of the radiated sound;

$$\begin{aligned} \zeta &= \sqrt{(1 - M_{\text{flow}} \cos \theta')^2 - \cos^2 \theta'} \\ &= \frac{\sin \theta_r}{1 + M_{\text{flow}} \cos \theta_r}; \end{aligned} \quad (\text{A.2})$$

$$\mu = \frac{\sin \theta'}{\zeta} = \frac{\sqrt{(1 + M_{\text{flow}} \cos \theta_r)^2 - \cos^2 \theta_r}}{\sin \theta_r}. \quad (\text{A.3})$$

Next, when the source is inside the mean flow ($h \neq 0$), the second correction is

required, which is written as [92]

$$\begin{aligned} \left| \frac{p_{c0p}(h \neq 0)}{p_{c0p}(h = 0)} \right| &= \frac{\sin \theta_m}{\sin \theta'} \sqrt{[1 + \sigma(\mu - 1)][1 + \sigma(\mu^3 - 1)]} \\ &= \frac{1 + M_{\text{flow}} \cos \theta_r}{\mu} \\ &\times \frac{\sin \theta_m}{\sin \theta_r} \sqrt{[1 + \sigma(\mu - 1)][1 + \sigma(\mu^3 - 1)]} \end{aligned} \quad (\text{A.4})$$

where

$$\sigma = \frac{h}{r_m \sin \theta_m}. \quad (\text{A.5})$$

In addition, when the thickness of the shear layer is sufficiently large compared with the wavelength of the radiated sound, the additional correction is required, which is represented as [92]

$$\begin{aligned} \left| \frac{p_{c\infty p}}{p_{c0p}} \right| &= \frac{2\sqrt{\zeta} \sin \theta' (1 - M_{\text{flow}} \cos \theta')}{\zeta + (1 - M_{\text{flow}} \cos \theta')^2 \sin \theta'} \\ &= \frac{2\sqrt{\mu} (1 + M_{\text{flow}} \cos \theta_r)}{(1 + M_{\text{flow}} \cos \theta_r)^2 + \mu} \end{aligned} \quad (\text{A.6})$$

where $p_{c\infty p}$ [Pa] and p_{c0p} [Pa] is the corrected sound pressures when the shear layer is sufficiently thick and thin compared with the wavelength of the radiated sound. Note that the correction is independent of the distance h .

Using Eqs. (A.1)-(A.6), the corrected sound pressures p_{c0p} and $p_{c\infty p}$ are obtained as [92]

$$\begin{aligned} \left| \frac{p_{c0p}}{p_{\text{mic}}} \right| &= \left| \frac{p_{c0p}(h = 0)}{p_{\text{mic}}} \right| \left| \frac{p_{c0p}(h \neq 0)}{p_{c0p}(h = 0)} \right| \\ &= \frac{(1 + M_{\text{flow}} \cos \theta_r)^2 + \mu}{2(1 + M_{\text{flow}} \cos \theta_r)^2 \mu^2} \\ &\times \frac{\sin \theta_m}{\sin \theta_r} \sqrt{[1 + \sigma(\mu - 1)][1 + \sigma(\mu^3 - 1)]} \end{aligned} \quad (\text{A.7})$$

and

$$\begin{aligned} \left| \frac{p_{c\infty p}}{p_{\text{mic}}} \right| &= \left| \frac{p_{c0p}}{p_{\text{mic}}} \right| \left| \frac{p_{c\infty p}}{p_{c0p}} \right| \\ &= \frac{1}{1 + M_{\text{flow}} \cos \theta_r} \frac{\sin \theta_m}{\sin \theta_r} \\ &\times \sqrt{\frac{[1 + \sigma(\mu - 1)][1 + \sigma(\mu^3 - 1)]}{\mu^3}}. \end{aligned} \quad (\text{A.8})$$

Figure A.1 shows the level difference of the corrected SPLs $|p_{c0p}|$ [dB] between the cases where $h \neq 0$ and $h = 0$ calculated at M_{flow} of (a)0.1, (b)0.2, and (c)0.3 using Eq. (A.4). The figures indicate that the calculated level differences where $h = 0.25, 0.3$, and 0.4 m are within ± 1 dB from the difference with h of 0.35 m for all the Mach numbers. This means that the corrected sound pressure $|p_{c0p}(h \neq 0)|$ where $0.25 < h \leq 0.4$ is within ± 1 dB from the level with h of 0.35 m.

Figure A.2 shows the level difference of the corrected SPLs between $|p_{c\infty p}|$ and $|p_{c0p}|$ calculated using Eq. (A.6) in the wind tunnel experiment ($h = 0.35$ m). The thickness of the shear layer can be ignored in correcting the sound pressure of the measured aerodynamic sound because the level difference is less than 1 dB even in the case of $M = 0.3$.

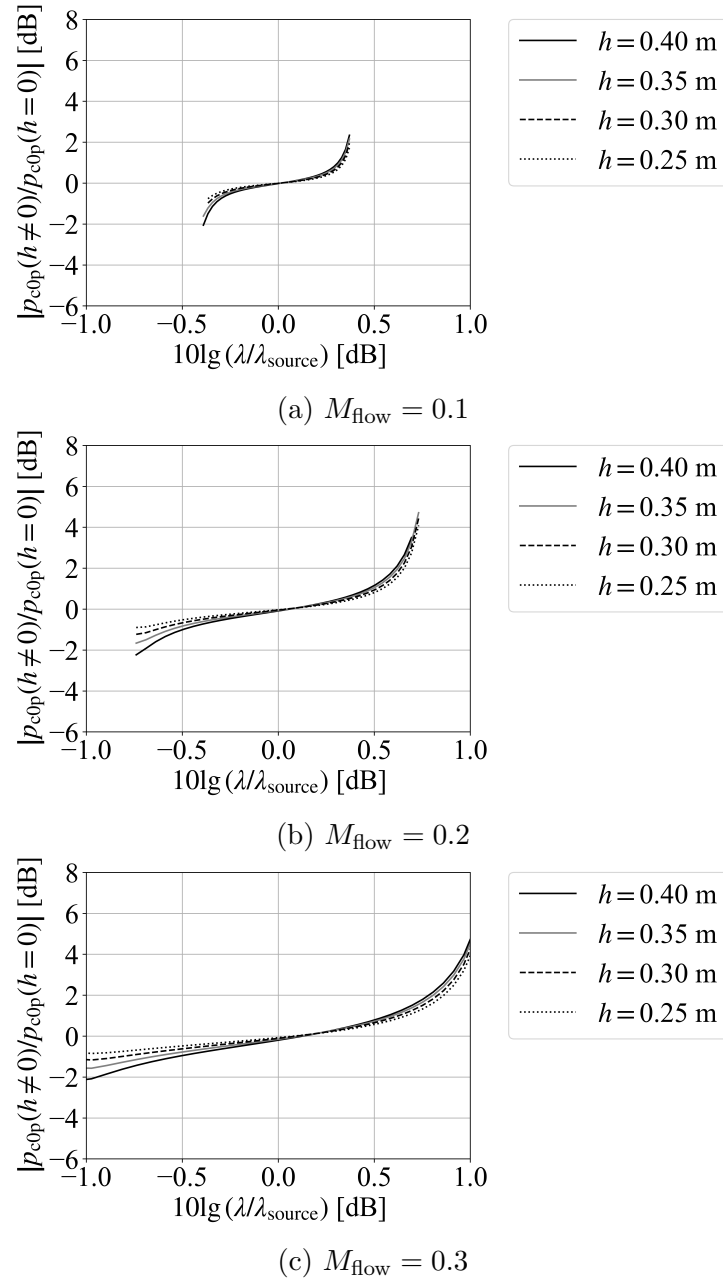


Figure A.1: Calculated level difference of the corrected SPLs $|p_{\text{cop}}(h \neq 0)/p_{\text{cop}}(h = 0)|$ [dB] between $h \neq 0$ and $h = 0$.

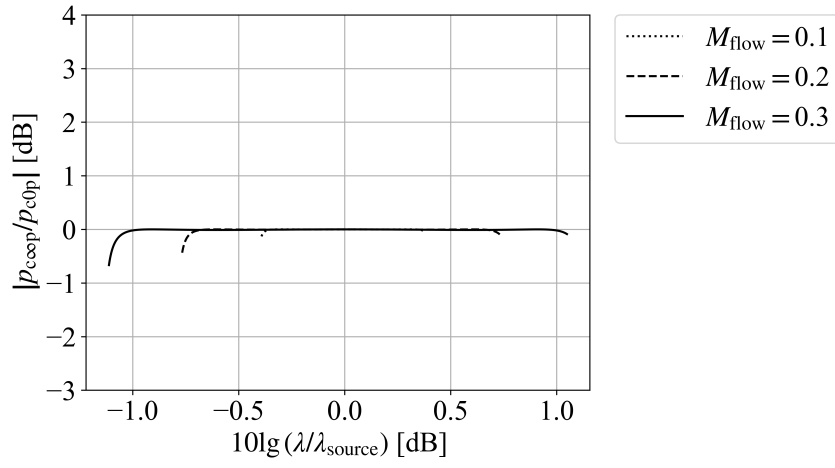


Figure A.2: Level difference of the corrected SPLs $|p_{c\infty p}/p_{c0p}| \text{ [dB]}$ between the cases where a shear layer is sufficiently thick and thin compared with the wavelength of the radiated sound ($h = 0.35 \text{ m}$).

Appendix B

Validity of approximations in deriving sound pressure

$\tilde{p}_n$ is defined as

$$\tilde{p}_n \equiv -i \frac{\partial \varphi}{\partial t} \frac{\rho \tilde{a} \exp(-i\varphi)}{4\pi r'}. \quad (\text{B.1})$$

Using Eq. (5.20),

$$\frac{p_n}{\tilde{p}_n} = 1 - \frac{\frac{1}{r'} \frac{\partial r'}{\partial t}}{\frac{\partial \varphi}{\partial t}} i = 1 - \left(1 + \frac{M z_{Sn}}{\sqrt{(1-M^2)r^2 + z_{Sn}^2}} \right) \frac{V z_{Sn}}{\omega_S (r^2 + z_{Sn}^2)} i. \quad (\text{B.2})$$

The errors of amplitude and phase of sound pressure E_{amp} and E_{ph} on the approximation where

$$p_n / \tilde{p}_n \approx 1 \quad (\text{B.3})$$

are defined as

$$E_{\text{amp}} \equiv 20 \log \left| \frac{p_n}{\tilde{p}_n} \right| \quad (\text{B.4})$$

and

$$E_{\text{ph}} \equiv \frac{1}{2\pi} \arg \left(\frac{p_n}{\tilde{p}_n} \right), \quad (\text{B.5})$$

respectively.

Figure B.1 shows E_{amp} and E_{ph} using Eqs. (B.4) and (B.5) when source frequency is 20 Hz and $r = 7.5$ m. As long as the evaluation of railway noise from high-speed railway, $E_{\text{amp}} \approx 0$ and $E_{\text{ph}} \approx 0$ because the imaginary part of $p_n / \tilde{p}_n$ approaches 0 as ω_S or r increase, hence $p_n / \tilde{p}_n \approx 1$.

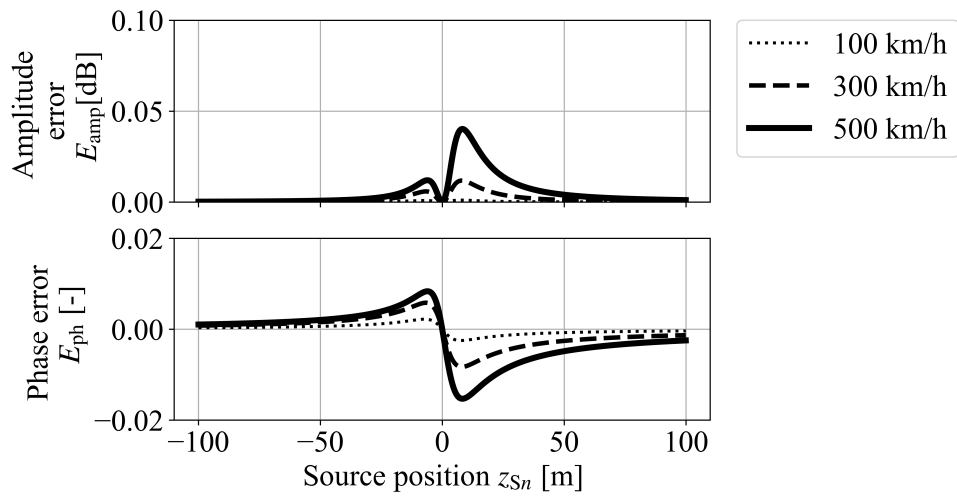
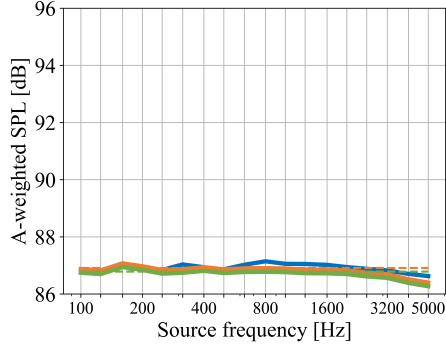


Figure B.1: Approximation error of amplitude E_{amp} and approximation error of phase E_{ph} (source frequency: 20 Hz, $r = 7.5$ m). From the figure, it can be approximated as $p_n/\tilde{p}_n \approx 1$.

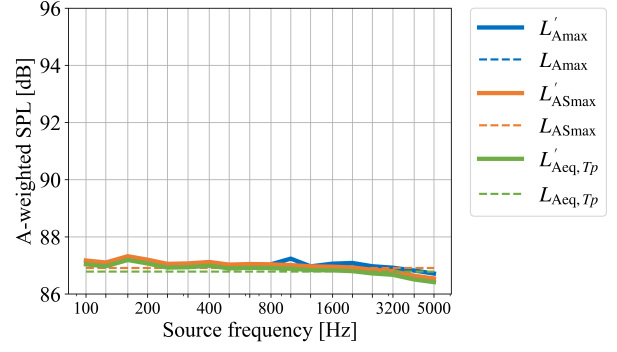
Appendix C

Changes of noise metrics

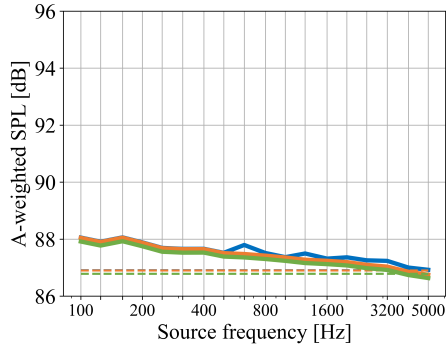
The detailed calculation results regarding the relationship between the source frequency and frequency modulation or amplitude modulation, as discussed in Chapter 5, are presented in this section.



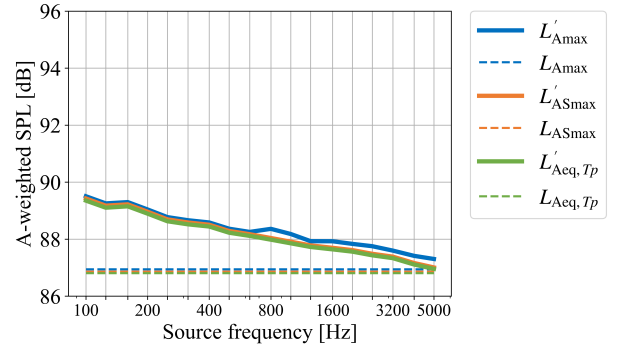
(a) source velocity: 10 km/h



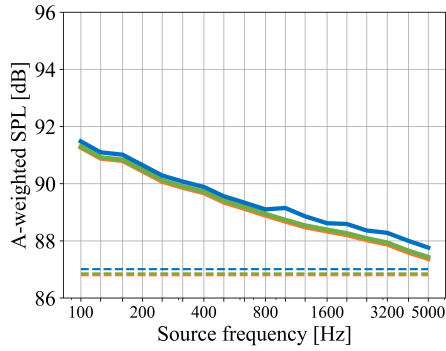
(b) source velocity: 100 km/h



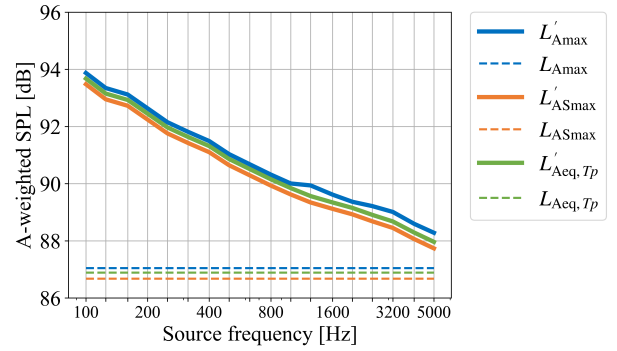
(c) source velocity: 200 km/h



(d) source velocity: 300 km/h

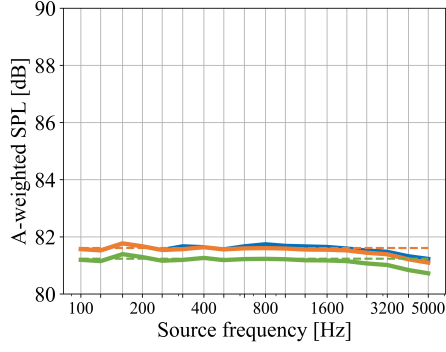


(e) source velocity: 400 km/h

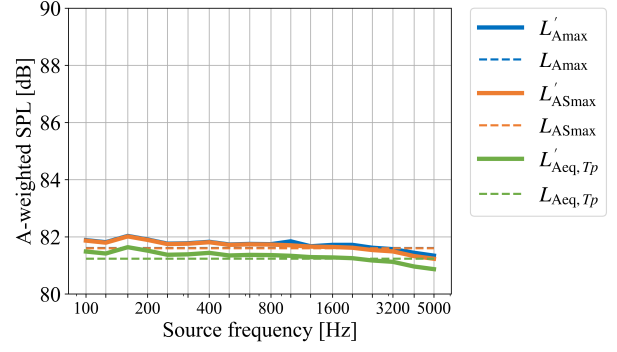


(f) source velocity: 500 km/h

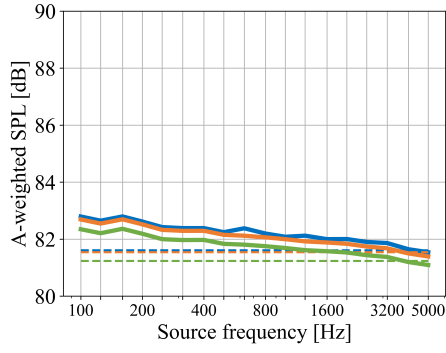
Figure C.1: Noise metrics for different source frequencies at $r = 7.5$ m.



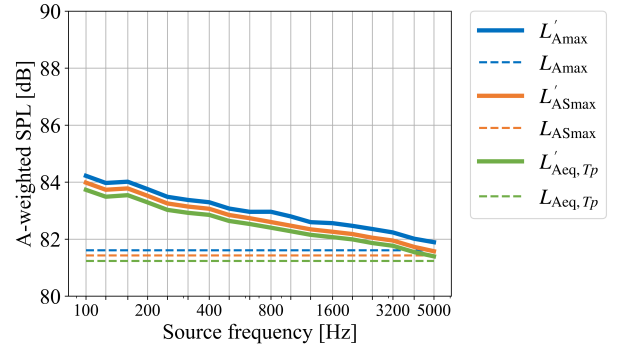
(a) source velocity: 10 km/h



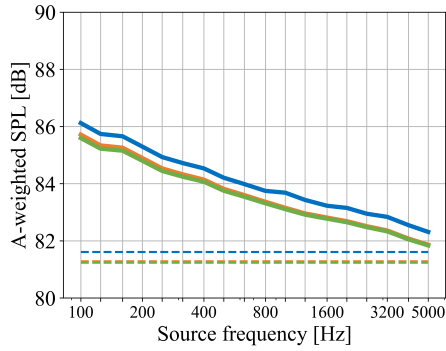
(b) source velocity: 100 km/h



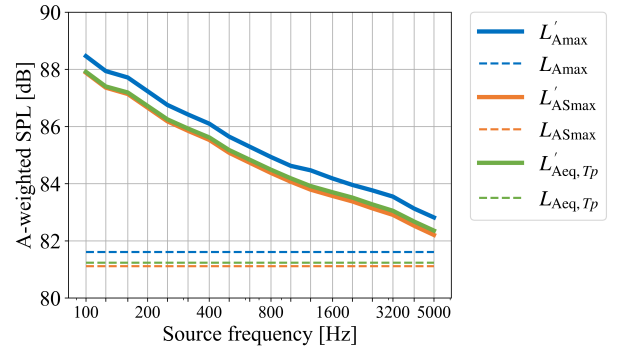
(c) source velocity: 200 km/h



(d) source velocity: 300 km/h

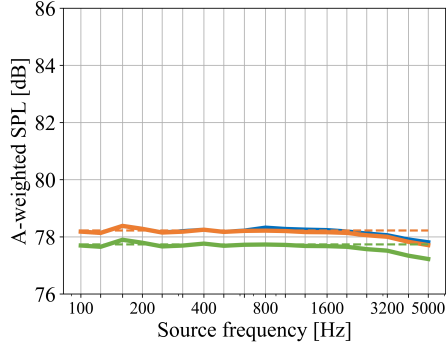


(e) source velocity: 400 km/h

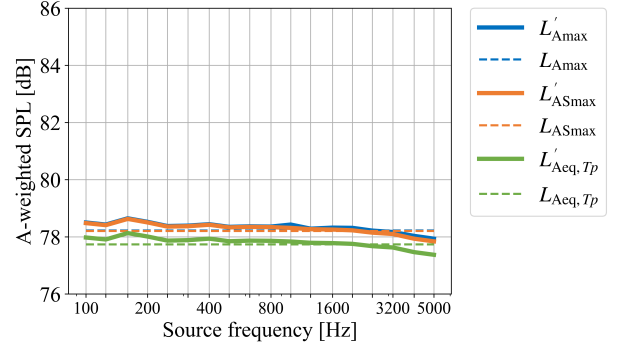


(f) source velocity: 500 km/h

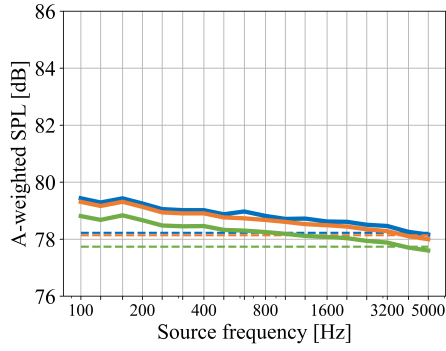
Figure C.2: Noise metrics for different source frequencies at $r = 25$ m.



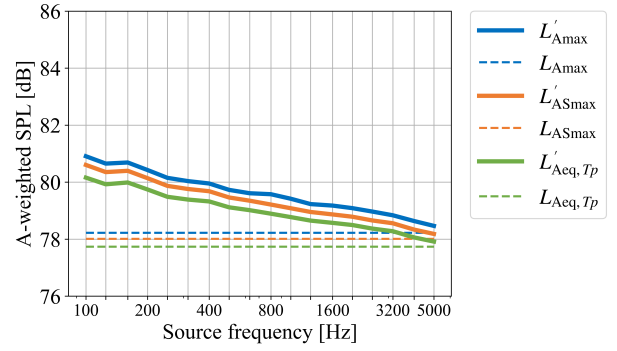
(a) source velocity: 10 km/h



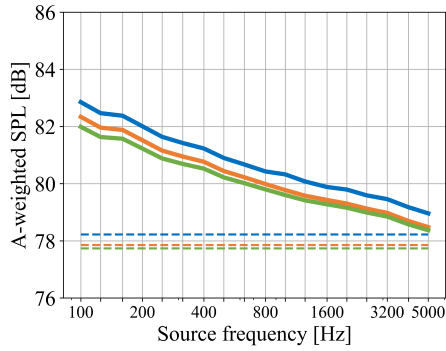
(b) source velocity: 100 km/h



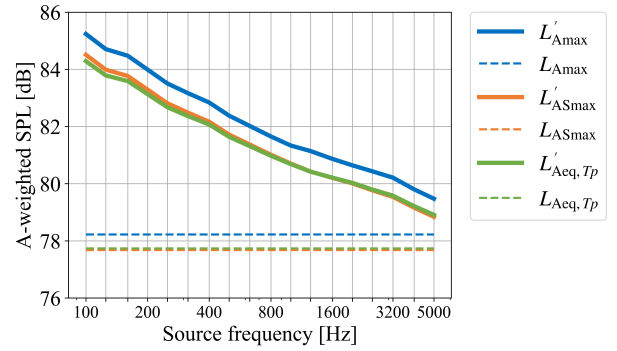
(c) source velocity: 200 km/h



(d) source velocity: 300 km/h

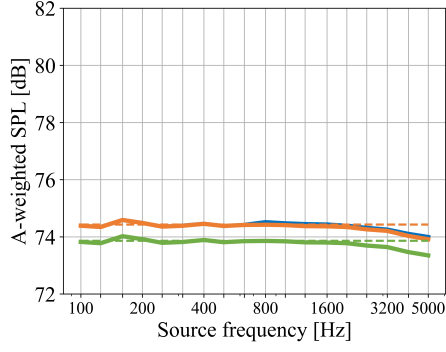


(e) source velocity: 400 km/h

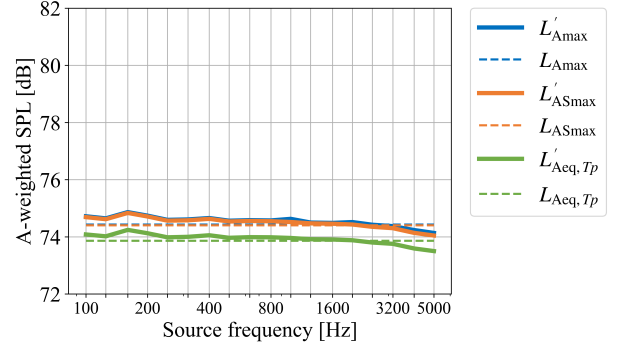


(f) source velocity: 500 km/h

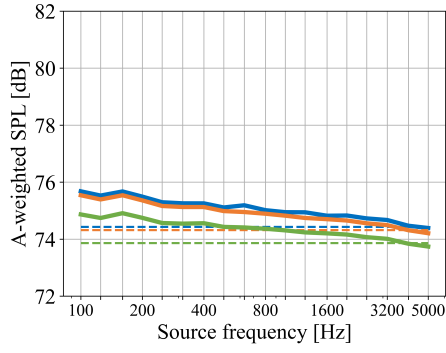
Figure C.3: Noise metrics for different source frequencies at $r = 50$ m.



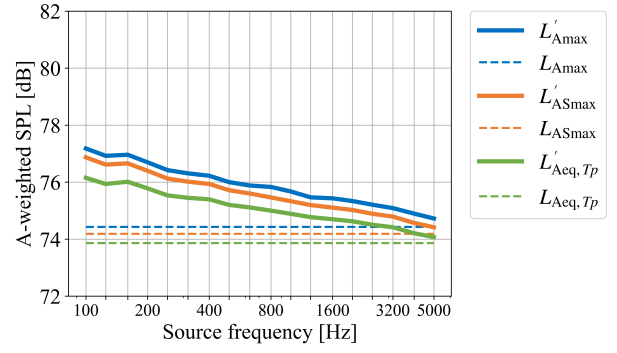
(a) source velocity: 10 km/h



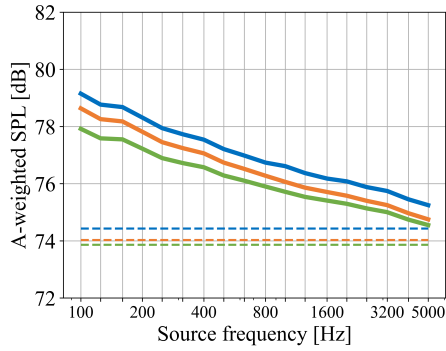
(b) source velocity: 100 km/h



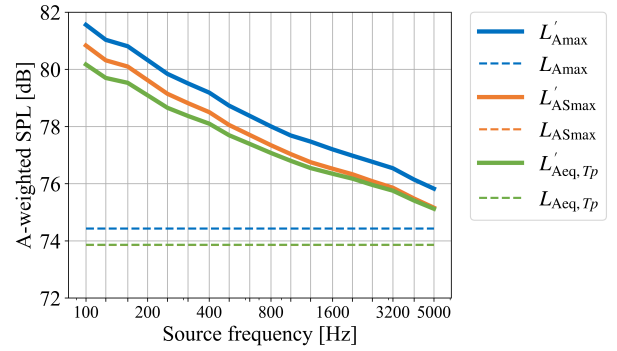
(c) source velocity: 200 km/h



(d) source velocity: 300 km/h

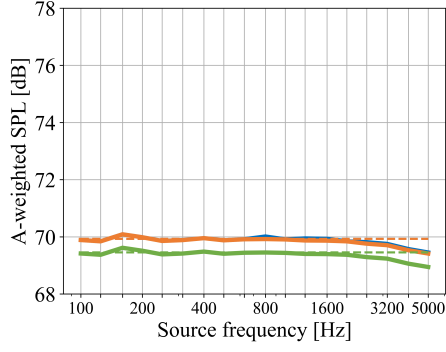


(e) source velocity: 400 km/h

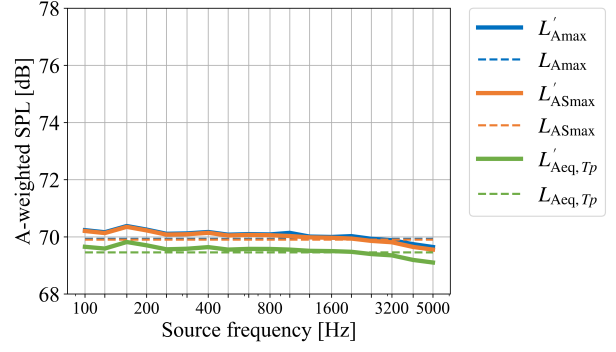


(f) source velocity: 500 km/h

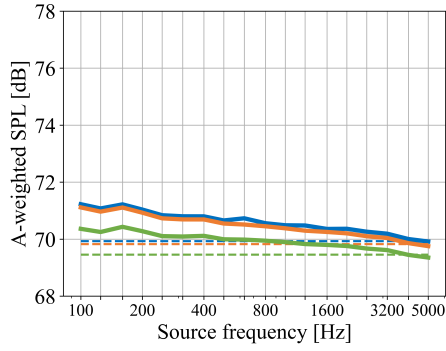
Figure C.4: Noise metrics for different source frequencies at $r = 100$ m.



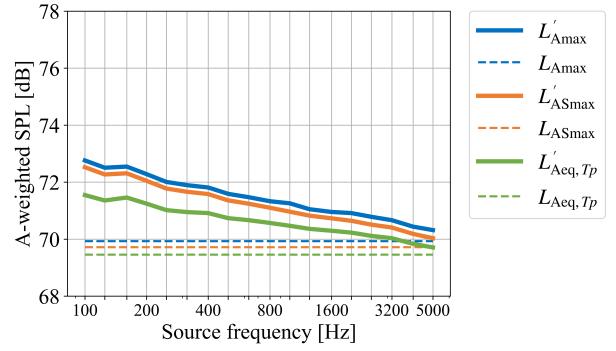
(a) source velocity: 10 km/h



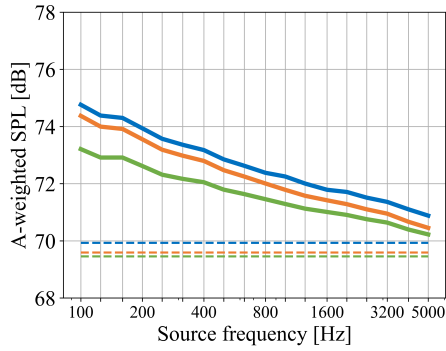
(b) source velocity: 100 km/h



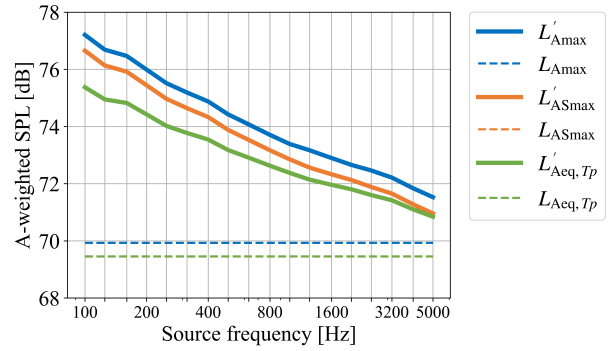
(c) source velocity: 200 km/h



(d) source velocity: 300 km/h

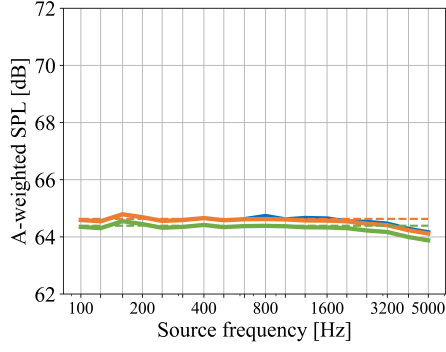


(e) source velocity: 400 km/h

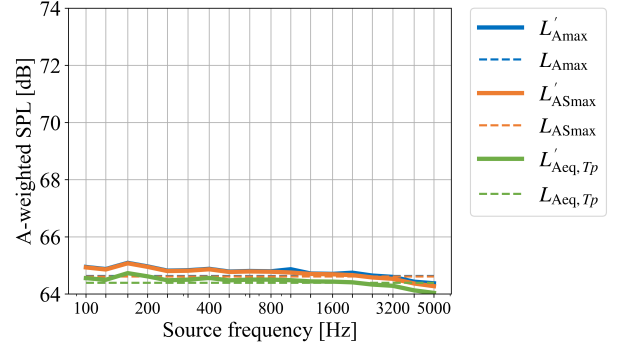


(f) source velocity: 500 km/h

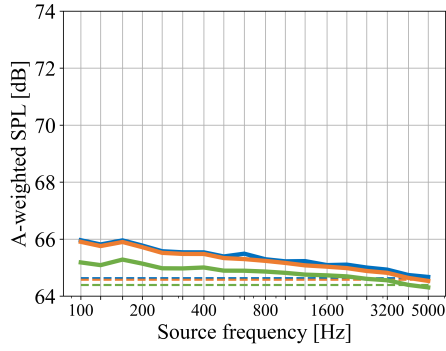
Figure C.5: Noise metrics for different source frequencies at $r = 200$ m.



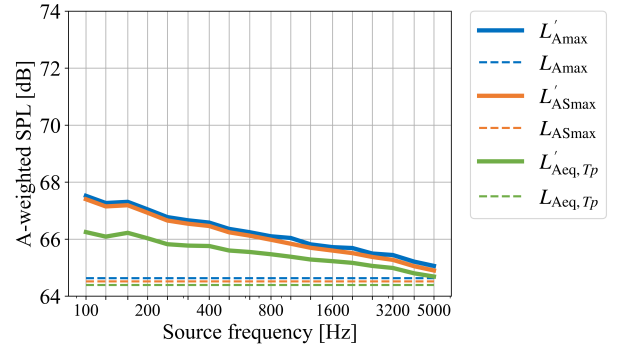
(a) source velocity: 10 km/h



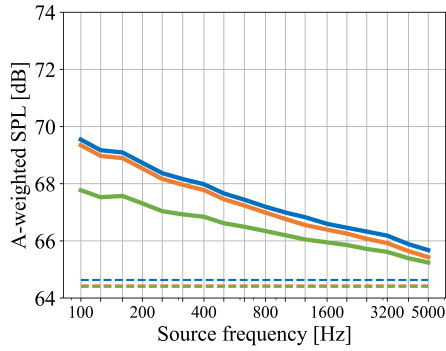
(b) source velocity: 100 km/h



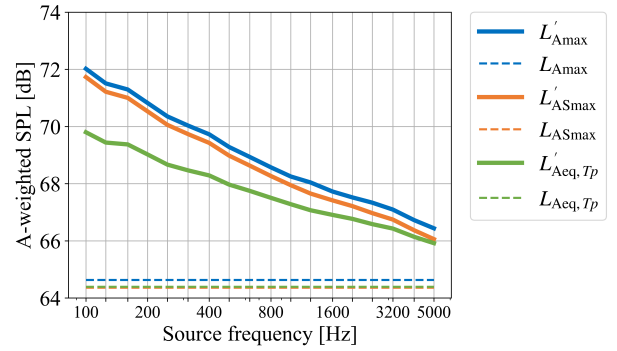
(c) source velocity: 200 km/h



(d) source velocity: 300 km/h



(e) source velocity: 400 km/h



(f) source velocity: 500 km/h

Figure C.6: Noise metrics for different source frequencies at $r = 400$ m.