<u>Technical Acoustics and Noise Control</u> *(lecture notes)*

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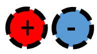
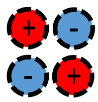
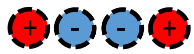
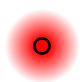
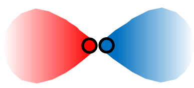
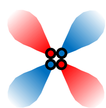
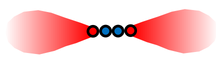
Content:

10.1. Simple sound source models

One important problem in the mechanical engineering noise control to determine the noise exposure in the neighbourhood of a sound source. Preparing this work, some important knowledge will be summarised about the sound sources in the next section.

Classifying sound sources based on the mathematic model of the sources:

The acoustic monopole is a sphere that can concentrically inflate and deflate its volume (breathing ping pong ball). The monopole creates sound by omnidirectional volumetric disturbances in the medium. Two monopole in close vicinity moving in opposite phase creates a dipole, and two opposite phase dipole will create a quadrupole. The four monopole placed along a straight line called longitudinal quadrupole, when the four monopole placed on the corners of a square called lateral quadrupole. The most important acoustic data of the basic acoustic source models are summarised in the following table.

Type of source	Monopole	Dipole	Lateral quadrupole	Longitudinal quadrupole
Build up				
Mechanism of the sound generation	$\frac{\partial q_v}{\partial t} \neq 0 \left[\frac{m^3}{s^2}\right]$	$\frac{\partial F_f}{\partial t} \neq 0 \left[\frac{N}{s}\right]$	$\frac{\partial \tau_f}{\partial t} \neq 0 \left[\frac{Pa}{s}\right]$	$\frac{\partial \sigma_f}{\partial t} \neq 0 \left[\frac{Pa}{s}\right]$
Sound intensity distribution	$I_m = \frac{\hat{q}_m^2 \rho_0 \omega^2}{32\pi^2 r^2 a}$	$I_d = \frac{\hat{q}_m^2 \rho_0 \omega^4}{8\pi^2 r^2 a^3} d^2 cos^2\theta$	$I_{q\,lat} = \frac{\hat{q}_m^2 \rho_0 \omega^6}{2\pi^2 r^2 a^5} d^2 h^2 cos^2\theta sin^2\theta cos^2\varphi$	$I_{q\,lon} = \frac{\hat{q}_m^2 \rho_0 \omega^6}{2\pi^2 r^2 a^5} d^2 h^2 cos^4\theta$
Radiation directivity				
Sound power	$P_m = \frac{\hat{q}_m^2 \rho_0 \omega^2}{8\pi a}$	$P_d = \frac{\hat{q}_m^2 \rho_0 \omega^4}{6\pi a^3} d^2$	$P_{q\,lat} = \frac{2\hat{q}_m^2 \rho_0 \omega^6}{15\pi a^5} d^2 h^2$	$P_{q\,lon} = \frac{2\hat{q}_m^2 \rho_0 \omega^6}{5\pi a^5} d^2 h^2$
Model law	$P_m \sim \frac{\rho_0 l_0^2 v_0^4}{a_0}$	$P_d \sim \frac{\rho_0 l_0^2 v_0^6}{a_0^3}$	$P_q \sim \frac{\rho_0 l_0^2 v_0^8}{a_0^5}$	
Acoustic efficiency	$\eta_m \sim Ma$	$\eta_d \sim Ma^3$	$\eta_q \sim Ma^5$	
Flow characteristics	Fluctuating volume flow rate	Non-steady low around solid body	Fluid mechanical shear layer	
Example	gunshot, internal comb. engine intake, exhaust, loudspeaker in box	Air grill noise, flute, naked loudspeaker	Free jet, wake noise	

The most important acoustic data of the elementary acoustic source models

Classifying sound sources based on physical mechanism of sound generation:

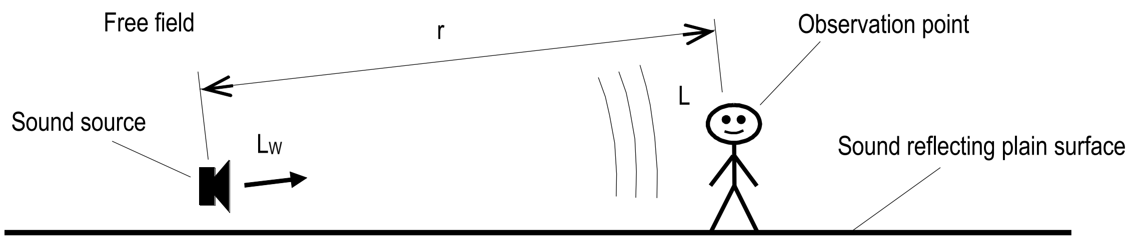
- Sound radiated by the vibration of solid body (e.g.: vibrating guitar string, loudspeaker membrane)
- Flow generated noise (e.g.: whistling telegraph wire, high speed free jet noise, flute sound)
- Thermal noise sources (e.g.: turbulent flame noise)
- Other sound source processes (e.g.: photo-acoustic effects, the noise of an electrostatic discharge)

Classifying sound sources based on geometric extent of the source:

- Point source: A sound source can take as point source when the characteristic size of the source in all three direction of the space coordinates is much smaller, than the distance between the source and observation point. (E.g.: MP3 player loudspeaker 0.5m far, electric locomotive 500m far.)
- Line source: A sound source can take as line source when the characteristic size of the source in two direction of the space coordinates is much smaller, than the distance between the source and observation point. (E.g.: overcrowded motorway.)
- Surface radiator: A sound source can take as surface radiator when, the characteristic size of the source in one direction of the space coordinates is much smaller, than the distance between the source and observation point. (E.g.: mobile gas turbine power station box surface 2m far, bubbling water surface in a wet cooling tower.)
- Volumetric radiator: A sound source can take as surface radiator when, the characteristic size of the source in any direction of the space coordinates is comparable to the distance between the source and observation point. (E.g.: turbulent flame close, multi floor open industrial plant (oil refinery plant).)

Point source:

One of the most frequently used type of sound source in the engineering noise control is the point source. In acceptable distance every real size source can take as point source. The goal of the mathematic model is to determine the sound pressure level in free field at given sound power level and distance from the point source.



The calculation of the sound field of a point source in free acoustic environment

The simplifications during the derivation are the same, applied in linear acoustics (the medium is a homogeneous, inviscid and non heat conducting, continuum, isentropic elementary thermodynamic process, the medium is in static rest, the amplitudes are small) and the environment of the source is a free field, the source is an omnidirectional point source (point monopole).

- In a homogeneous, non-moving medium the sound ray are straight lines. In general case the sound ray is the envelope curve of the sound speed vectors. For a point source the sound ray channel is a cone where the cross sectional area will proportional with second power of the radius
- The free acoustic field means, that the sound propagation will not be blocked with acoustically non-transparent objects.
- In inviscid, non heat conducting medium there is no losses during sound propagation.
- The omnidirectional criteria means, that in a given distance from the source the sound intensity is independent form the direction.

- The wave fronts of a point source are concentric spherical surfaces. Far enough from the origin, in the close vicinity of the observation point the wave can approximate as a plain wave, where the sound pressure and the particle velocity are in phase. The intensity for free plain wave sound propagation,

$$I = \frac{p_{eff}^2}{\rho_0 a}$$

Based on a simple energetic phenomena, the relation between the sound power radiated by the source (P), the intensity (I) and radiation area (A),

$$P = IA = \frac{p_{eff}^2}{\rho_0 a} A$$

The radiation area (A) at (r) distance from the source is the surface of the sphere of radius (r). In practise the radiation area usually is not the complete surface of the sphere, because free acoustic environment partly bordered with reflecting sections. For example when a car traveling the on the road, made of concrete, the sound rays starting from the car to the road surface, will reflect back, and continue their way to the rest free section. Partly narrowing the totally free space will not limit the application of the original point source sound field model. But we must take into consideration to narrow the propagation area will increase the intensity at the rest. To narrow the area, free for sound propagation, and the connected increase of intensity will take into consideration with a directivity coefficient (D),

$$D = \frac{A_{sphere\ total}}{A_{sphere\ real}}$$

The value of directivity coefficient (D), for totally free space is 1 (airplane after taking off), for half space is 2 (source placed on a sound reflecting plane surface), for a quarter space is 4 (source placed in an edge of two perpendicular, plane sound reflecting surfaces) and for a one to eight space is 8 (source placed in a corner of three perpendicular, plane sound reflecting surfaces). If the boarder surface is a sound absorber, the incident sound ray will be absorbed, there is no increase of intensity, and the sound field in the free section will not be effected. For example a porous soil surface with dense (thick) grass can take approximately as an absorber surface. So the relation among the power (P), effective sound pressure (p_{eff}), distance from the source (r), and directivity coefficient (D) is,

$$P = I\frac{4\pi r^2}{D} = \frac{p_{eff}^2}{\rho_0 a}\frac{4\pi r^2}{D}$$

For practical calculation let's turn to level notation. Both side of the expression divide with 10^{-12}-el (at right side this is $400/(2\cdot 10^{-5})^2$), take the 10 base logarithm and multiple with 10,

$$10lg\frac{P}{10^{-12}} = 10lg\frac{p_{eff}^2}{(2\cdot 10^{-5})^2} + 10lg\frac{400}{\rho_0 a} + 10lg\, r^2 - 10\lg D + 10\lg 4\pi$$

The term at left is the sound power level (L_W), at right first is the sound pressure level (L). In air, at technical normal state (t_0= 20ºC, p_0= 1bar) the product of the equilibrium density and the speed of sound, rounded to integer, is 408 [kg/m^{2}s], so the second term at right approximately negligible. The sound pressure level (L), at (r) meter far from the sound source is,

$$L = L_W - 10lg\, r^2 + 10\lg D - 11 \quad [dB]$$

Comments:

- In a free space, partly bordered with sound reflecting surfaces the sound pressure level (L) far from the point source will depend on the sound power level radiated by the source (L_W), the distance between the source and observation point (r) and the directivity coefficient (D).

- To double the sound power (e.g.: doubled the number of the same sound sources) will result 3dB sound pressure level increase. Adding one more source to the same ten, the increase in sound pressure level will be 10lg(11/10)≈ 0,4dB, which is slightly audible, and practically negligible.

- At constant sound power level, double the distance from the sound source will result 6dB decrease, and half the distance will result 6dB increase in sound pressure level.

- In a sound field of a point source at increasing distance the main reason of the sound pressure level decrease is that, the same power distributed on a bigger spherical surface, and not the dissipation.

- In engineering noise control one of the effective noise control method to keep a suitable distance between the noise source and the protected area.

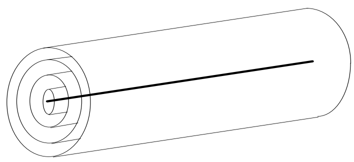
- To double the directivity coefficient (D) will result 3dB sound pressure level increase. If the boundaries are sound absorbing surfaces, there is no change in sound pressure level.

- The formula derived above, can apply from 1…4 meter till 100…400 meter depending on the frequency. Very close to the sound source the plane wave approximation will be problematic and the sound pressure and particle velocity will not be in phase. Far from the source the sound attenuation caused by dissipative effects will spoil the accuracy of the model. Most of the mechanical engineering noise control problems lay inside the application are of the formula.

Line source:

Point sources following each other in a close vicinity along an infinite long straight line will form line source. Depending on the phase behaviour of the point sources, the line sources can share into coherent and incoherent types. The purpose of the derivation is to determine the sound pressure level in a free field at given sound power level and distance from the source. Except the source geometry, the simplifications applied in the model are the same used at point source.

Coherent line source: A series of point sources, radiating the same frequency, amplitude and initial phase along an infinite long straight line will form coherent line source. The coherent line source will create an axial symmetric sound field, the wave surfaces will be concentric cylindrical surfaces.



The axial symmetric sound field around the coherent line source

The relation between the sound power per unit length radiated by the source (P'), distance (r), directivity coefficient (D) and the intensity (I) in the sound field is,

$$P'l = IA = I\frac{2\pi rl}{D}$$

Where (l) is length of the investigated section (source and sound field), and directivity coefficient (D) is,

$$D = \frac{A_{cylinder\ total}}{A_{cylinder\ real}}$$

Far enough from the source, where the sound propagation can approximate as plane wave propagation, and the sound pressure and the particle velocity are in phase, the relation among the power per unit length (P'), effective sound pressure (p_{eff}), distance (r), and directivity coefficient (D) is,

$$P' = \frac{p_{eff}^2}{\rho_0 a}\frac{2\pi r}{D}$$

Change the formula to levels,

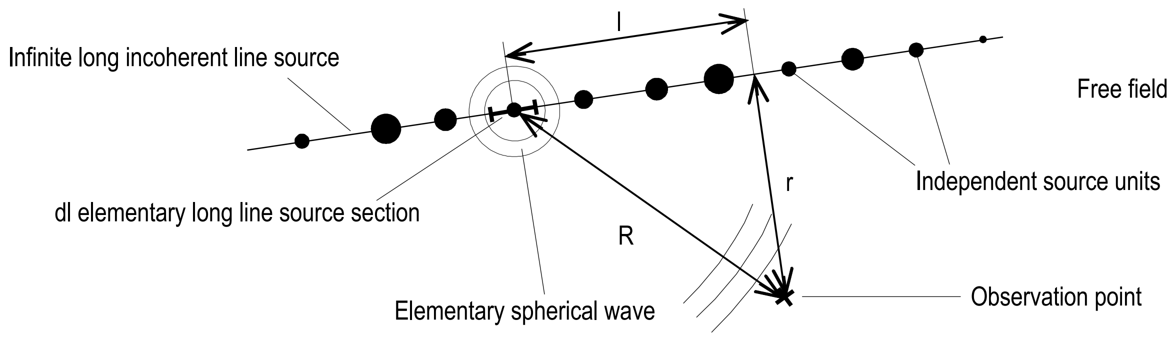
$$10lg\frac{P'}{10^{-12}} = 10lg\frac{p_{eff}^2}{(2\ 10^{-5})^2} + 10lg\frac{400}{\rho_0 a} + 10\lg r - 10\lg D + 10\lg 2\pi$$

In air, at technical normal state (where $\rho_0 a \approx 408$ [kg/m^{2}s]), the sound pressure level (L_{cl}), (r) meter far from the coherent line source is,

$$L_{cl} = L'_W - 10lg\,r + 10\lg D - 8\ \ [dB]$$

The coherent line source is a simple physical concept, mathematically easy to derive, but quite difficult to find example, so its practical importance is limited.

Incoherent line source: A series of independent point sources, radiating different frequency, amplitude and initial phase along an infinite long straight line will form incoherent line source. An over jammed motorway, a long railway train or a pressurised steam pipeline after a throttling valve approximately can take as incoherent line source. To derive the axial symmetric sound field of the incoherent line source we have to summarise the elementary intensities in the observation point, radiating by the elementary long sections of the incoherent line source. The elementary long line source section will create elementary spherical waves.



The elementary spherical wave and its effect in the observation point, created by the elementary section of the incoherent line source (elementary independent point source)

The elementary long (dl) line source section radiates (P'dl) elementary sound power. The elementary sound intensity (dI), created by the (P'dl) elementary sound power of the point like source in the observation point is,

$$dI = \frac{P'Ddl}{4\pi R^2}$$

where,

$$R^2 = r^2 + l^2$$

To reduce the number of variables let substitute radius (R) in the elementary intensity (dI) expression,

$$dI = \frac{P'D}{4\pi}\frac{dl}{r^2 + l^2}$$

To solve the differential equation let integral both side. To simplify the solution divide the numerator and denominator in the second ratio at right with (r^2), and suppose that the radiated sound power per unit length (P') and directivity coefficient (D) are constant along the line source,

$$I = \int_0^I dI = \frac{P'D}{4\pi r}\int_{-\infty}^{\infty}\frac{d\left(\frac{l}{r}\right)}{1+\left(\frac{l}{r}\right)^2} = \frac{P'D}{4\pi r}\left[arctg\left(\frac{l}{r}\right)\right]_{-\infty}^{\infty} = \frac{P'D}{4\pi r}\left(\frac{\pi}{2}-\left(-\frac{\pi}{2}\right)\right) = \frac{P'D}{4r}$$

Far enough from the source, the sound wave, passing the observation point, is a free plain wave, where the sound pressure and the particle velocity are in phase. The relation among the power per unit length (P'), effective sound pressure (p_{eff}), distance (r), and directivity coefficient (D) is,

$$\frac{p_{eff}^2}{\rho_0 a} = I = \frac{P'D}{4r}$$

Let's apply level notation,

$$10lg\frac{p_{eff}^2}{(2\ 10^{-5})^2} + 10lg\frac{400}{\rho_0 a} = 10lg\frac{P'}{10^{-12}} + 10\lg D - 10\lg r - 10\lg 2$$

In technical normal state air (where $\rho_0 a \approx 408$ [kg/m^{2}s]), the sound pressure level (L_{icl}), (r) meter far from the incoherent line source is,

$$L_{icl} = L'_W - 10lg\, r + 10\lg D - 6\ \ [dB]$$

Comments:

- Except the distance dependence, the comments summarised at the point sources, are valid for the line sources too.
- For both of the line sources double the distance from the sound source will result 3dB decrease, and half the distance will result 3dB increase in sound pressure level.
- To increase the distance between source and observer is not so efficient noise control method for line sources than for point sources.

11.2. Test questions and solved problems

T.Q.1. Based on a simple energetic relation let derive the sound pressure level (L), at (r) meter far from a point source, radiating sound power level (L_W) and placed in free field. What are the application limits of the formula? Give example for point source!

T.Q.2. What is the difference between the coherent and incoherent line sources?

S.P.1. A radial flow fan transports air from the free space to a room. To increase the ventilated volume flow rate the rotational speed of the fan was increased with 50%. Calculate the resultant sound pressure level change, in free field at a fixed distance from the suction opening, if the other circumstances of the sound generation and propagation do not change.

Solution: The dominant noise source mechanism of the ventilator is the fluctuating force acting on air particles (creating the turbulent flow around the fan blade), which can take as a dipole (see the table). The 50% increase in the rotational speed means one and half time bigger characteristic speed of the flow. Based on the model law of the dipole, and the formula of the sound pressure level distribution around a point source, the sound pressure level change,

$$\Delta L = L_2 - L_1 = L_{W2} - 10lgr_2^2 + 10\lg D_2 - 11 - L_{W1} + 10lgr_1^2 - 10\lg D_1 + 11 =$$

Except the sound power level (L_W), all variables remain constant,

$$L_{W2} - L_{W1} = 10lg\frac{P_2}{P_0} - 10lg\frac{P_1}{P_0} = 10lg\frac{P_2}{P_1} = 10lg\frac{Const.\cdot\frac{\rho_2 l_2^2 v_2^6}{a_2^3}}{Const.\cdot\frac{\rho_1 l_1^2 v_1^6}{a_1^3}} = 10lg\frac{v_2^6}{v_1^6} =$$

$$60lg\frac{v_2}{v_1} = 60lg\frac{1{,}5v_1}{v_1} = 60lg1{,}5 \approx 10{,}6\ [dB]$$

S.P.2. A point source operating in a free field that bounded with sound absorbing plane surface, is moved to a corner (intersection of 3 sound reflecting perpendicular planes), during the distance from the sound source is increased 4 times bigger and the radiated sound power is doubled. Calculate the resulted sound pressure level change!

Solution:

$$\Delta L = L_2 - L_1 = L_{W2} - L_{W1} - 10lg\, r_2^2 + 10lg\, r_1^2 + 10\lg D_2 - 10\lg D_1 - 11 + 11 =$$

$$10lg\, P_2/P_1 - 20lg\, r_2/r_1 + 10lg\, D_2/D_1 = 10lg2 - 20lg4 + 10lg8 = 0\ \ dB$$

S.P.3. Two neighbouring axial flow fan transport air from a room, placed on the ground level and in the middle of a 320m long and 10 floor high concrete wall building, into the connected open air space. The observation point placed 55m from the fans, is on the sound reflecting surface in front of the building. Between the fan and the observation point there is a garage building, partly blocks the sound propagation. Determine the A-weighted sound pressure level in the observation point. The sound power radiated by the fans outlet (P_{1oct} and P_{2oct}), the insertion loss (ΔL_{inoct}) to characterise the sound propagation blockage and the relative levels of the A-weighting curve (ΔL_{Aoct}) as a function of the octave-band frequencies can be found in the following tabulation.

f_{oct} [Hz]	250	500	1k	2k	4k
P_{1oct} [W]	0,1	0,5	0,1	0,01	0,001
P_{2oct} [W]	0,5	0,1	0,05	0,01	0,005
ΔL_{inoct}	6	8	11	15	19
ΔL_{Aoct} [dB]	-8,6	-3,2	0	1,2	1

Solution:

f_{oct} [Hz]	250	500	1k	2k	4k
$P_{1+2oct} = P_{1oct} + P_{2oct}$ [W]	0,6	0,6	0,15	0,02	0,006
$L_{W1+2oct} = 10lg(P_{1+2oct}/P_0)$ [dB] where: $P_0 = 10^{-12}$ W	117,8	117,8	111,8	103	97,8
$L_{oct} = L_{W1+2oct} - 10lgr^2 + 10lgD - 11 = L_{W1+2oct} - 10lg55^2 + 10lg4 - 11 =$ [dB]	78	78	72	63,2	58
$L_{oct} - \Delta L_{inoct}$ [dB]	72	70	61	48,2	39
$L_{oct} - \Delta L_{inoct} + \Delta L_{Aoct}$ [dB]	63,4	66,8	61	49,4	40

$L_A = 10lg(10^{6,34} + 10^{6,68} + 10^{6,1} + 10^{4,94} + 10^{4}) \approx$ **69,2** [dB(A)]

(Note: See details about the A-weighting in the measurement syllabus and more details later in the lecture notes)
