Characteristics of Low-Frequency Pressure Waves Radiated From a Train Passing an Open Section*

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Abstract
Characteristics of low-frequency pressure waves radiated from a train passing a Shinkansen viaduct were examined from field measurements based on the manual for measuring low-frequency noise issued by Ministry of the Environment Government in October 2000, using a low-frequency sound level meter (NA-18 A) manufactured by Rion Co. Ltd. Measurements proved that low-frequency noise comprises a hydrodynamic pressure variation and an acoustic pressure wave. The hydrodynamic pressure variation is designated as the train passing pseudo-sound and the acoustic pressure wave is designated as the low-frequency pressure wave. The low-frequency pressure wave is emitted from a line source and is proportional to the 4th–5th power of train velocity and inversely to the first power of the distance from the source to the observation point.

Key words: Pressure Wave, Open Section, Field Measurement, Infrasound, High-Speed Railway

1. Introduction

Ministry of the Environment Government of Japan (MOE) issued the “Measurement manual for low-frequency noise(1)” in October 2000, in which the noise between the center frequencies of 1 Hz to 80 Hz in the one-third octave band is defined as low-frequency noise. Frequency components higher than 100 Hz can be included in a human voice and are clearly recognizable as sound. On the other hand, frequency components below 100 Hz are rarely recognizable as sound, but are felt as an oppression or vibration(2). Frequency components of less than 20 Hz are designated as infrasound(3).

The influences of low-frequency noise are divisible into two categories: human-influencing and object-influencing(4). Human-influencing can be further categorized as those having a physiological influence and those exerting a psychological influence. Because no such loud low-frequency noise causes physiologic effects in general living environments, it is conceivable that no physiological problems exist, but it is believed that some influence on sleep occurs(5). The value of sound pressure level that elicits complaints differs greatly according to individual susceptibilities for psychological influence(6) and fittings response for object influence(7).

Since sound pressure level (SPL) causes complaints that differ greatly for psychological influence and object influence, a public standard such as an environmental standard or a regulatory standard is not applicable to low-frequency noise(8).
Low-frequency noise is classifiable into various types by its origin. For example, continuous low-frequency noises are emitted from factories and outdoor air-conditioner units. In addition, intermittent low-frequency noises are emitted from roads, airplanes and ships. Furthermore, impulsive low-frequency noises are emitted by explosions.

Pressure variations observed near tunnel entrances of railways are given as an example of a source of environmentally influential low-frequency noise in the MOE report. A micro-pressure wave constitutes the typical low-frequency noise emitted from a tunnel portal. In addition, there are some other low-frequency noises emitted from it like a tunnel entry/exit wave, tunnel continuous wave, train passing branch wave, etc. (where a "branch" indicates a vertical shaft, a horizontal shaft, an inclined shaft, a short side branch, etc.).

Low-frequency noises are observed not only near tunnel portals. They are observed at open-air sections near the wayside of railway. At a fixed point in an open-air section, pressure variations are detectable as a train passes by. A simple mathematical model of this phenomenon is given as the following:

\[
p = \frac{1}{4\pi} \frac{q'[t - (R/c_0)]}{R^2(1 - M \cos \theta)} + \frac{q}{4\pi} \frac{(\cos \theta - M)U}{R^3(1 - M \cos \theta)}
\]

where 
- \( q \): source strength
- \( q' \): a time derivative of \( q \)
- \( U \): a moving velocity
- \( M \): \((= U/c_0, \ c_0\) the speed of sound) is a Mach number
- \( t \): time
- \( R \): a distance between the source and the observer
- \( \theta \): an angle between the direction of the velocity vector, and that of the position vector of the observer relative to the source at the time of sound emission.

The first and second terms on the right hand side of Eq. (1) respectively represent an acoustic pressure wave and an hydrodynamic pressure variation (pseudo-sound). The second term decreases faster than the first term as the distance \( R \) increases. Therefore, we can regard the first term as the far-field term and the second term as the near-field term. In general, the observer points are assumed to be in the intermediate region, where the far-field and near-field terms are of the same order of magnitude.

Naturally, the actual conditions of low-frequency noise from the trains in an open-air section are much more complex than those represented by Eq. (1). Notwithstanding, it can be said that the pressure variations attributable to a train’s passing consist of acoustic pressure waves and hydrodynamic pressure variations. That fact has been confirmed using field test results.

For this study, we define the low-frequency noise observed in an open-air section as the following.

1. **Train passing pseudo-sound**: The near-field hydrodynamic pressure variation. This is pressure variation observed at a fixed point in an open-air section as a result that quasi-steady pressure fields around a train (mainly, at a train nose, tail, and pantograph shield) move as the train passes. This is not a wave phenomenon.

2. **Low-frequency pressure wave**: The far-field acoustic pressure wave. This is low-frequency acoustic pressure variations below approximately 100 Hz radiated from a train. These acoustic pressure waves are caused by sources whose strength varies with time such as unsteady disturbed flow around the train and vibrating surfaces of a viaduct structure.

Studies of this phenomenon and the countermeasures for a train passing pseudo-sound have been made through theoretical analyses of incompressible potential flow, model experiments, and field measurements. The main characteristics of the train passing...
pseudo-sound are the following:

(1) The magnitude of pressure variation is proportional to the square of the train velocity and inversely proportional to the square of the distance from the center of the train to a measurement point.

(2) The main frequency components are below about 5 Hz.

(3) The train passing pseudo-sound can be modeled by an incompressible potential flow in which a source is placed at the nose of the train and a sink at the tail.

These characteristics correspond to that for the second term of Eq. (1).

On the other hand, the characteristics of low-frequency pressure waves such as velocity dependence, distance attenuation, spectra, sound sources, etc. remain to be clarified.

2. Purpose of research

This study is intended to clarify the characteristics of the low-frequency pressure wave emitted when a train passes an open-air section by conducting field measurements near a Shinkansen viaduct.

Since no official document specified the method of measuring low-frequency noise in Japan until 2000, an original method in the railway industry has been applicable to measure mainly micro-pressure wave and train passing pseudo-sound. In the original method, low-frequency noise is measured with an infrasound pressure-level meter (XN-12A; Rion Co. Ltd.) and the measured data are recorded as time histories of sound pressure, not the sound pressure level, from which the peak value of sound pressure is obtainable. The Ministry of the Environment of Japan issued a MOE manual in 2000, which was the first official document specifying the method of measuring low-frequency noise in Japan. Subsequently, many measurements have been conducted by local public offices based upon the MOE manual(10). It is predictable that future measurements will also be performed based upon the MOE manual. Furthermore, because the low-frequency pressure wave is a steady irregular vibration wave pattern, we might be able to clarify its characteristics from the time histories of the sound pressure level, not from that of the sound pressure. Therefore, we conducted measurements based upon procedures in the MOE manual and tried to grasp the physical characteristics of the low-frequency pressure wave from the measured data in this paper. This is the first report of an attempt to clarify the characteristics of the low-frequency pressure wave from the measured results based upon the MOE manual. We also point out some problems of clarifying the characteristics of the low-frequency noise emitted during a train’s passage (especially train passing pseudo-sound) from the data measured based on MOE manual.

3. Outline of measurements

Figure 1 shows an outline of the measurement. The viaduct height is approximately 7 m, with 2-m-high simple straight sound shield walls attached to both sides. The track structure is a non-ballasted slab type and the track alignment is straight. Three measurement points were at the down-line side of the track and located at 12.5 m (M1, M4), 25 m (M2, M5) and 50 m (M3, M6), respectively, from the viaduct centerline. We placed infrasound pressure level meters (flat in 0.2–1000 Hz; XN-12A; Rion Co. Ltd.) at measurement points M1–M3 and low-frequency sound pressure level meters (flat in 1–100 Hz; NA-18A; Rion Co. Ltd.) at measurement points M4–M6. Therefore, we placed two different instruments, XN-12A and NA-18A, at the same 12.5 m, 25 m, or 50 m measurement points respectively. The XN-12A is an instrument to measure the low-frequency noise in a railway industry conventionally. In this paper, time histories of pressure waves are only shown from results obtained by XN-12A. The NA-18A is an instrument for measuring low-frequency noise.
based on the MOE manual. Table 1 shows measured specifications of high-speed trains (called "Shinkansen" in Japan).

According to the MOE manual, measured data obtained from low-frequency sound-pressure level meters (NA-18A) are recorded as time histories of G-weighted sound pressure level (SPL) and 1/3-octave band filtered SPL, from which we are able to obtain the peak values of G-weighted SPL and 1/3-octave band SPL (spectrum). The time constant in integration for sound pressure level is 1 s (SLOW). The results from time histories of G-weighted SPL are available in the Appendix.

<table>
<thead>
<tr>
<th>Train</th>
<th>Maximum velocity (km/h)</th>
<th>Cross-sectional area (m²)</th>
<th>Nose length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>240</td>
<td>12.2</td>
<td>5.5</td>
</tr>
<tr>
<td>B</td>
<td>240</td>
<td>12.2</td>
<td>7.6</td>
</tr>
<tr>
<td>C</td>
<td>240</td>
<td>10.1</td>
<td>4.75</td>
</tr>
<tr>
<td>D</td>
<td>275</td>
<td>11.2</td>
<td>9.1</td>
</tr>
<tr>
<td>E</td>
<td>275 (340)</td>
<td>10.3</td>
<td>6.0</td>
</tr>
<tr>
<td>F</td>
<td>240</td>
<td>14.1</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Table 1 Specifications of trains

Fig. 1  Schematic of field measurement

4. Results

4.1 Time histories of measured waveform and SPL

Figure 2 shows the time histories of pressure waves of low-frequency noise measured at the points M1, M2 and M3 for a down-train of type D running at the speed of 246 km/h. The origin of the horizontal axis in Fig. 2 differs from that in Fig. 3 and Fig. 9. From Fig. 2, it is readily apparent that two large pressure variations observed at about 5 s and 9 s correspond to the near field pressure variations caused by the passing of the nose and tail of the train. The pattern of the pressure variation exhibits positive and negative pressure on the nose and the negative and positive on the tail. This phenomenon is the train passing pseudo-sound\(^{(15)}\) as modeled by the incompressible potential flow. Pressure waves of small amplitude occurring during the passage of the train intermediate part correspond to the low-frequency pressure wave\(^{(17)}\).
Figure 3 shows an example of 1/3 octave band SPL measured at the point M4 (12.5 m) when a down-train of type D passes at the speed of 246 km/h. Figure 3 shows only waves of 1, 2, 4, 8, 16, 31.5, and 63 Hz corresponding to octave band center frequency to clarify the figure. Figure 3 shows that a peak appears later as the 1/3 octave band center frequency is lower in the time histories of 1/3 octave band SPL of 4, 2 and 1 Hz. We infer that this is attributable to the influence of the time constant in integration for a sound-pressure level meter\(^{(21)}\). Time histories in Fig. 3 were measured at point M4 (12.5 m) and two distinct peaks appear in the 2 and 4 Hz waveforms, which are attributable to the passing of the nose and tail of the train. However, no peaks can be attributed to the passing of the nose and tail of the train in the time history of 1/3 octave band SPL of 1 Hz, probably because of the influence of a filter of a sound-pressure level meter\(^{(22)}\). This illustrates a problem in clarifying the characteristics of low-frequency noise, especially the train passing pseudo-sound, from data measured based on the MOE manual. On the other hand, no distinct peak due to the passing of the nose and tail of the train appears in the time histories of 1/3 octave band SPL greater than 8 Hz. In addition, SPLs greater than 8 Hz show only one gradual flat-top peak.

4.2 1/3 octave band sound-pressure level

Figure 4 shows an example of measured 1/3 octave band SPLs for the low-frequency noise from the down-train of the train type E. The times at which different 1/3 octave band SPLs show maximum values do not necessarily coincide mutually during the train’s passage. Therefore, we cannot regard Fig. 4 as an instantaneous spectrum. From Fig. 4 we can see that a trough exists at 2–8 Hz; 6–8 Hz at M4 (12.5 m point), 4–6 Hz at M5 (25 m point), and 2–3 Hz at M6 (50 m point). The SPL on the left side of this trough decreases as the frequency increases from 1 Hz and the SPL on the right side of this trough increases as the frequency increases up to 20–30 Hz. However, the SPL remains roughly constant above 20 Hz and does not include a tonal component. We consider that the SPL on the left side of the trough corresponds to the train passing pseudo-sound and that, on the right side, it corresponds to the low-frequency pressure wave for the following reasons. In the time histories of 1/3 octave band SPL measured at point M4 (12.5 m) in Fig. 3, two peaks appear in the time histories between approximately 2–4 Hz due to the train passing pseudo-sound,
which corresponds to the passing of the nose and tail. In addition, the magnitude of the peaks becomes smaller as the 1/3 octave band center frequency increases. Such a trend corresponds to the results shown in Fig. 4, which were measured at M4 (12.5 m) below 6 Hz, those measured at M5 (25 m) below 4 Hz, and those measured at M6 (50 m) below 2 Hz. On the other hand, time histories of the 1/3 octave band SPL above 8 Hz in Fig. 3 exhibit one gradual flat-top peak because of the low-frequency pressure wave. The magnitude of each 1/3 octave band center frequency SPL is approximately equal. This trend corresponds to results in Fig. 4 measured at M4 (12.5 m) above 30 Hz, those measured at M5 (25 m) above 20 Hz, and those measured at M6 (50 m) above 20 Hz.

4.3 Velocity dependence

Figure 5 shows the velocity dependence of the maximum value of the F-weighted SPL (flat in 1-100Hz) and 1/3 octave band SPL (only three bands of 1, 31.5 and 80 Hz are shown as examples) for the low-frequency noise. The solid lines represent the $U^3$ law and the $U^6$ law, where $U$ is the train speed. The $U^3$ law is applicable to rolling noise and structural vibration noise (23); the $U^6$ law is applicable to aeroacoustic noise (23). The velocity dependence of the train passing pseudo-sound represented by sound pressure level, not by the pressure amplitude, is $U^4$. Table 2 shows the theoretical velocity dependence for each noise source. The velocity dependence of the SPL of the center frequency $f_i$ is defined by the factor "n" as follows:

$$L_i\left(f_i\right) - L_2\left(f_i\right) = 10\log\left(\frac{U_1}{U_2}\right)^n$$

(2)
where \( L_1 \) is the sound pressure level of the center frequency \( f_1 \) at train velocity \( U_1 \); also, \( L_2 \) is the sound pressure level of the center frequency \( f_2 \) at train velocity \( U_2 \).

The SPL magnitude depends on the train type. The velocity dependence of the SPL was calculated using data of train type E which ran over a comparatively wide speed range and was showed in Fig. 6. From Fig. 6, the velocity dependence of frequency components above 2 Hz measured at point M6 (50 m) is represented by a \( U^4 - U^3 \) law. The same velocity dependence is visible in frequency components higher than 5–8 Hz measured at point M4 (12.5 m) and M5 (25 m). As described above, the low-frequency pressure wave dominates these frequency components. Therefore, we infer that the main noise source of the low-frequency pressure wave is based on the \( U^4 - U^3 \) law. However, the velocity dependence of aeroacoustic noise emitted from the train is about \( U^6 \) according to wind tunnel test results for audible noise\(^{(24)}\). On the other hand, the obtained velocity dependence is lower than the \( U^6 \) law, perhaps because SPL includes not only aeroacoustic noise, but also the rolling noise, structural vibratory noise, etc. However, we cannot determine exactly which noise source generates the low-frequency pressure wave. Candidates of noise sources are structural vibratory noise and aeroacoustic noise (the rails and wheels are so small that it is difficult to infer that they are the sources of the low-frequency pressure waves under 100 Hz).

It is conceivable from Fig. 6 that frequency components below 2 Hz measured at point M6 (50 m) and those below 5–8 Hz measured at point M4 (12.5 m) and M5 (25 m) are generated by the train passing pseudo-sound from the discussion in section 4.2. The velocity dependence of the train passing pseudo-sound is the \( U^3 \) law (see Table 2). However, the result in Fig. 6 deviates greatly from \( U^4 \) because the time interval of the train passing pseudo-sound is short and the time history of SPL measured using the low-frequency level meter (NA-18A) is distorted greatly by the influence of its filter\(^{(23)}\). The maximum value of the 1/3 octave band SPL is obtained from this greatly distorted time history. This is also an obstacle to clarification of the characteristics of low-frequency noise that is generated when the train passes, especially the train passing pseudo-sound.

To clarify the difference of low-frequency pressure waves by train type the graph of high-frequency components in Fig. 5, e.g. 80 Hz, is useful. From the result measured at point M6 (50 m), the following order of magnitude is apparent.

Train A (inverse triangle) > Train D (diamond) > Train E (double circle)

It is conceivable that this order of magnitude results from the train sectional area, train shape, train weight, etc. Nevertheless, it remains unclear which effect is dominant based only on these measured data. It can be said that there is a difference by train type means that the low-frequency pressure wave might be reducible by application of some countermeasures to the train.

<table>
<thead>
<tr>
<th>Low-frequency pressure wave</th>
<th>Pressure amplitude</th>
<th>Pressure level</th>
<th>( n ) value cf. Eq.(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train passing pseudo-sound</td>
<td>( U^2 )</td>
<td>( U^4 )</td>
<td>4</td>
</tr>
<tr>
<td>Rolling</td>
<td>( U^{1.5} )</td>
<td>( U^3 )</td>
<td>3</td>
</tr>
<tr>
<td>Structure</td>
<td>( U^{1.5} )</td>
<td>( U^3 )</td>
<td>3</td>
</tr>
<tr>
<td>Aeroacoustic</td>
<td>( U^3 )</td>
<td>( U^6 )</td>
<td>6</td>
</tr>
</tbody>
</table>
4.4 Distance attenuation

Figure 7 shows the distance attenuation of the peak value of the F-weighted SPL and 1/3 octave band SPL (only three bands of 1, 31.5 and 80 Hz are shown as examples) for the low-frequency noise from down-trains of type D and type E. Table 3 shows the theoretical distance attenuation for each noise source\(^{(25)}\). The distance attenuation of SPL of the center frequency \(f_i\) is defined by the factor "m" as follows:

\[
L_1(f_i) - L_2(f_i) = 10 \log \left( \frac{r_1}{r_2} \right)^m
\]

where \(L_1\) is the sound pressure level of the center frequency \(f_i\) at distance \(r_1\) and \(L_2\) is the sound pressure level of the center frequency \(f_i\) at distance \(r_2\).

The distance \(r\) is that between the center of the viaduct and each measurement point. Figure 8 shows the factor \(m\) for each datum. From Fig. 8, the factor \(m\) is about -1 for frequency components greater than approximately 8 Hz. Comparing this result and the factor \(m\) in Table 3, we infer that the frequency components greater than approximately 8 Hz are the low-frequency pressure waves, whose sources are classified as a line source of the low-frequency pressure wave. This inference coincides with the result obtained from the velocity dependence described in section 4.3. The frequency component below about 8 Hz might depend on the passing train pseudo-sound; in that case, the factor \(m\) is -4. However, Fig. 8 shows that the results deviate greatly from -4. Apparently, the cause is attributable to the filter of the measuring instrument as noted in section 4.3.
Table 3 Distance attenuation for various sources

<table>
<thead>
<tr>
<th>Source型</th>
<th>Pressure amplitude</th>
<th>Pressure level</th>
<th>$m$ value cf. Eq.(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train passing pseudo-sound (Hydrodynamic pressure variation)</td>
<td>Point source</td>
<td>$1/r^2$</td>
<td>$-40 \log r$</td>
</tr>
<tr>
<td></td>
<td>Line source</td>
<td>$1/r$</td>
<td>$-20 \log r$</td>
</tr>
<tr>
<td>Low-frequency pressure wave (Acoustic pressure wave)</td>
<td>Point source</td>
<td>$1/r$</td>
<td>$-20 \log r$</td>
</tr>
<tr>
<td></td>
<td>Line source</td>
<td>$1/\sqrt{r}$</td>
<td>$-10 \log r$</td>
</tr>
</tbody>
</table>

5. Conclusions

Field measurements were performed on the wayside low-frequency noise of high-speed railway trains (Shinkansen) emitted in an open-air section. Measurements were taken according to the manual issued by the Ministry of the Environment of Japan in October 2000. From those measured results, the following conclusions were drawn:

(1) Time histories of 1/3 octave band SPL consist of two patterns. Although time histories below 2–8 Hz exhibit two distinct peaks attributable to the passing of the nose and tail of the train, no peak in the time histories greater than 2–8 Hz is attributable to the passing of the nose and tail.

(2) The spectra exhibit a trough at 2–8 Hz. The SPL on the left side of the trough corresponds to the train passing pseudo-sound; that on the right side corresponds to the low-frequency pressure wave. We summarize the characteristics of the train passing pseudo-sound and the low-frequency pressure wave in Table 4.

(3) It is plausible that a main noise source of the low-frequency pressure wave is aeroacoustic noise, but some contributions exist from the rolling noise and structural noise.

(4) Depending on the train type, differences exist in the magnitude of the low-frequency pressure wave.

(5) It is difficult to separating the train passing pseudo-sound from the data measured according to the MOE manual.

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Table 4 Characteristics of train passing pseudo-sound and low-frequency pressure wave

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Train passing pseudo-sound</th>
<th>Low-frequency pressure wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cause of pressure variation</td>
<td>Hydrodynamic pressure variation</td>
<td>Acoustic pressure wave</td>
</tr>
<tr>
<td>Range of frequency</td>
<td>1-8 Hz</td>
<td>8 – 80 Hz</td>
</tr>
<tr>
<td>Source distribution</td>
<td>Point source</td>
<td>Line source</td>
</tr>
<tr>
<td>Dependency of sound level peak value on train velocity</td>
<td>(U^4)</td>
<td>(U^4 - U^5)</td>
</tr>
<tr>
<td>Dependency of sound level peak value on distance from the center of viaduct</td>
<td>(r^{-4})</td>
<td>(r^{-1})</td>
</tr>
</tbody>
</table>

# Values in parentheses represent theoretical ones, not measured ones

Appendix

The measured quantities based on the MOE manual were \(G\)-weighted SPL and 1/3-octave band SPL of the low-frequency noise. However, we described only the results of 1/3-octave band SPL in the body of this paper to clarify the characteristics of the low-frequency pressure wave. We described the remaining results of \(G\)-weighted SPL in the Appendix.

(1) Time histories of measured SPL

Figure 9 shows the time histories of \(G\)-weighted SPL of the low-frequency noise measured at points M4, M5 and M6 when a down-train of type D passed at 246 km/h. For comparison, Fig. 9 also shows time histories of \(F\)-weighted SPL. The \(G\)-weighted SPL increases as the train’s nose approaches, then remains approximately constant while the intermediate part of the train passes, and decreases as the tail of the train goes away. Although the \(F\)-weighted SPL exhibits two distinct peaks corresponding to the passing of the nose and tail, the \(G\)-weighted SPL shows only one gradual flat-top peak, which can be explained in the following manner. According to previous studies, the train passing pseudo-sound consists mainly of frequency components approximately below 2–6 Hz\(^{(15)}\). Therefore, because the frequency characteristic of \(G\)-weighting has a peak at 20 Hz and decreases markedly below 5 Hz, the train passing pseudo-sound makes little contribution to the \(G\)-weighted SPL. The same effect of \(G\)-weighting is visible in the time histories of SPL at M6 (50 m). That is, although the \(F\)-weighted SPL is larger than the \(F\)-weighted SPL at M4 (12.5 m) and M5 (25 m), the \(G\)-weighted SPL is larger than the \(F\)-weighted SPL at M6 (50 m). This is because the \(G\)-weighted SPL is amplified by 9dB at 20 Hz.

(2) Velocity dependence

Figure 10 shows the velocity dependence of the maximum value of the \(G\)-weighted SPL for the low-frequency noise. The solid lines represent the \(U^3\) law and the \(U^6\) law, where \(U\) is the train speed. The magnitude of \(G\)-weighted SPL depends on train types. From Fig. 10, the velocity dependence of the \(G\)-weighted SPL is between the \(U^3\) law and the \(U^6\) law. Consequently, we consider that the maximum value of the \(G\)-weighted SPL depends on both the train passing pseudo-sound (velocity dependence is \(U^4\) law) and the low-frequency pressure wave (velocity dependence is \(U^4 - U^5\) law). Based only on these results, however, it is indeterminable which contribution is greater. Nevertheless, as stated in (1), the frequency components around 20 Hz contribute greatly to the \(G\)-weighted SPL. It
is conclusive that the low-frequency pressure wave contributes to the maximum value of the G-weighted SPL.

![Graph](image)

**Fig. 9** Time history of G-weighted pressure level at train passage measured by NA-18A

**Fig. 10** Relation between train velocity and peak value of G-weighted pressure level measured by NA-18A

**(3) Distance attenuation**

Figure 11 shows the distance attenuation of the maximum value of the G-weighted SPL for the low-frequency noise from down-trains of type D and type E. The broken lines represent the $-10\log r$ law and the $-20\log r$ law, where r is the distance between the centerline of the viaduct and the measurement points. From Fig. 11, the distance attenuation of the maximum of the G-weighted SPL coincides with the $-10\log r$ law. Consequently, we infer that the G-weighted SPL depends on the low-frequency pressure wave, whose sources are classified as the line source.

**Fig. 11** Relation between train velocity and peak value of G-weighted pressure level measured by NA-18A

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