Visualization of pass-by noise by means of moving frame acoustic holography

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The noise generated by pass-by test (ISO 362) was visualized. The moving frame acoustic holography was improved to visualize the pass-by noise and predict its level. The proposed method allowed us to visualize tire and engine noise generated by pass-by test based on the following assumption; the noise can be assumed to be quasistationary. This is first because the speed change during the period of our interest is negligible and second because the frequency change of the noise is also negligible. The proposed method was verified by a controlled loud speaker experiment. Effects of running condition, e.g., accelerating according to ISO 362, cruising at constant speed, and coasting down, on the radiated noise were also visualized. The visualized results show where the tire noise is generated and how it propagates. © 2001 Acoustical Society of America. [DOI: 10.1121/1.1404976]
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I. INTRODUCTION

Vehicle pass-by noise level is one of major concern to car manufacturers because the maximum noise level is strictly controlled by international regulations. Several measuring standards, e.g., ISO 362' and SAE J14702 specify methods of measuring the maximum noise level during the pass-by test. Being able to see where noise is generated and how it propagates would be very helpful to reduce the pass-by noise. This paper addresses the visualization of noise generated by the pass-by test.

Line array methods3–16 have been widely used for localizing the noise sources of high-speed trains and moving vehicles. The linear, the cross-shaped, and the X-shaped arrays have been employed. However, the methods have inherent drawbacks. The methods only find the locations of noise sources because they estimate beam forming power on the assumed source plane. On the other hand, the nearfield acoustic holography (NAH)17 provides all useful acoustic variables in the entire volume of interest. However, in order to apply NAH to a moving noise source, a plane array of microphones has to be attached to the vehicle.18 The complexity and cost of this system limit the practical applicability of NAH to moving noise sources.

Moving frame acoustic holography (MFAH)19–21 combines the simplicity of the conventional line array methods and the ability of NAH. MFAH uses a sweeping line array of microphones. The relative motion between the noise source and the line array enables us to continuously sweep a sound field and produces the hologram of the scanned plane. When a line array of microphones is standing on the ground, this method enables us to visualize the noise generated by a moving source based on NAH. This is the advantage of MFAH. Effects of moving noise sources on an obtained hologram can be neglected for low Mach number.21 MFAH can be applied not only to a tonal component,19 but also to a coherent band-limited one.20

Although noise generated by a rolling tire on a dynamometer can be visualized by means of time domain acoustic holography (TDH),22 the demand to see or study the noise generated in the general situation of which a vehicle moves on a road never diminishes. This paper reports a method of visualization of pass-by noise. The operating condition of a vehicle must follow the way of which is defined in the pass-by noise measurement (ISO 362). MFAH cannot directly be applied to general transient source signals because the method assumes the hologram to be stationary in time. We propose a modified MFAH method so that it can be applied to a transient signal. In fact, this paper assumes the transient signal to be the sum of piecewise stationary signal. The applicability of the proposed method was verified not only by performing a controlled loud speaker experiment but also by comparing with the commercial STSF (spatial transformation of sound fields) system.23 Then, tire and engine noise during the pass-by test was visualized based on the proposed method. The period of the measurement was less than 0.5 second. The speed change is shown to be negligible during the period. The frequency change during the period was small enough to regard the radiated sound as a quasistationary. The sound pressure and the intensity distribution of tire and engine noise during the pass-by test were obtained. The effect of running condition, e.g., cruising with constant speed, accelerating according to ISO 362, and coasting down conditions on the radiated sound were visualized.

II. THEORETICAL BACKGROUND

A. Moving frame acoustic holography (MFAH) for pass-by noise

Moving frame acoustic holography (MFAH), which is originally proposed to increase the aperture size and the spatial resolution of a hologram, allows a line array of micro-
the noise sources to the measured time signal. MFAH provides the method to determine between the line array and the noise source enables us to phones continuously sweeps a sound field. The relative motion of the line array indicates the coordinate systems at \( t=0 \). The coordinate \((0,y_m,z_m)\) on the measurement coordinate system corresponds to \((x_m,0,z_m)\) on the hologram coordinate system. The right-hand figure shows the coordinate systems at \( t=t' \). Notice that the coordinate \((0,y_m,z_m)\) on the measurement coordinate system corresponds to \((S_{m,h}(t)+x_m+y_m,z_m)\) on the hologram coordinate system due to the relative motion. The dashed coordinate system denotes the measurement coordinate system at \( t=0 \).

FIG. 1. Three coordinate systems employed in moving frame acoustic holography and the relative coordinate transformation. The left-hand figure indicates the coordinate systems at \( t=0 \). The coordinate \((0,y_m,z_m)\) on the measurement coordinate system corresponds to \((x_m,0,z_m)\) on the hologram coordinate system. The right-hand figure shows the coordinate systems at \( t=t' \). Notice that the coordinate \((0,y_m,z_m)\) on the measurement coordinate system corresponds to \((S_{m,h}(t)+x_m+y_m,z_m)\) on the hologram coordinate system due to the relative motion. The dashed coordinate system denotes the measurement coordinate system at \( t=0 \).

phones continuously sweeps a sound field. The relative motion between the line array and the noise source enables us to measure both temporal and spatial information of the sound field simultaneously. However, this induces a Doppler effect to the measured time signal. MFAH provides the method to reconstruct spatial information (sound field) from the time signal so that the hologram of the scanned plane can be obtained. The transformation introduces three coordinate systems (Fig. 1). The reference coordinate \((x,y,z)\) is fixed to the ground (or acoustic medium). The measurement coordinate \([x_m,y_m,z_m]\), fixed to a line array of microphones, and the hologram coordinate \([x_h,y_h,z_h]\), fixed to the noise sources, are systems in relative motion (in \( x \) direction) with respect to the source, \( u_{m/h}(t)=u_m(t)-u_h(t) \) (see Fig. 1). We assume that the rate of change of relative velocity \( u_{m/h}(t) \) is negligible. Measured sound pressure by a line array of microphones \((x_m=0, z_m=z_H)\) can be expressed on the hologram coordinate,

\[
p_m(0,y_m,z_H;i) = p_h(S_{m,h}(t),y_h,z_H;i),
\]

where subscript \( m \) and \( h \) denote the pressure on the measurement coordinate and that on the hologram coordinate. The relative coordinate transformation,

\[
x_h = S_{m,h}(t) + x_m, \quad y_h = y_m \quad \text{and} \quad z_h = z_m,
\]

where \( S_{m,h}(t) = \int_0^t u_{m/h}(\tau) d\tau \), is used in Eq. (1). When the noise source moves and the line array is fixed, \( [u_{m/h}(t)] \), the wave front distribution is changed due to the source motion. The wave fronts in the forward direction are closer together than they would be if the source were stationary. In the backward direction, the wave fronts are farther apart. This moving effect causes errors on the obtained hologram. However, the errors are small enough to be neglected if the speed of noise sources is much less than the speed of sound \((M<0.1)\). See Ref. 21 for details. Since the speed of vehicle during pass-by test is the case therefore, MFAH could be applied to analyze the pass-by noise.

Let us start with the simplest case, so as to examine the possibility to extend MFAH to the case of our interest. Consider a moving microphone continuously scans the plane wave sound field whose magnitude is \( P_0 \). We assume that the frequency and the wave vector of the plane wave are \( f_{h0} \) and \((k_{h0},0,0)\). The hologram of this sound field is \( P_0 e^{ik_{h0}x_0} \). This can be reconstructed from the measured signal (by a moving microphone).

\[
p_h(x_h,y_h,z_H;i) = P_0 e^{ik_{h0}x_0} e^{-i2\pi f_{h0}t} = P_0 e^{ik_{h0}x_0} e^{-i2\pi f_{h0}t},
\]

Notice that the hologram of this sound field is \( P_0 e^{ik_{h0}x_0} \), which represents the spatial distribution of the sound field. This equation indicates that a sound field can be expressed as the multiplication of spatial \((P_0 e^{ik_{h0}x_0})\) and temporal information \((e^{-i2\pi f_{h0}t})\) in complex domain. When the microphone moves in \( x \) direction with speed \( u_{m/h}(t)=u_m(t) \), the measured pressure (time signal) preserves this property, but in different form, that is, (Fig. 2)

\[
p_m(0,y_m,z_H;i) = p_h(S_{m,h}(t),y_h,z_H;i) = P_0 e^{ik_{h0}x_0} e^{-i2\pi f_{h0}t},
\]

where the microphone is fixed at \((0,y_m,z_H)\) on the measurement coordinate. This equation conveys the idea that we can obtain the hologram (the complex envelope of the signal) whenever we measure the relative displacement of microphone \( x_h=S_{m,h}(t) \) and the frequency of sound field \( f_{h0} \). The hologram can be obtained by multiplying the complex conjugate of \( e^{-i2\pi f_{h0}t} \) by both sides of the equation.

This result can be extended to more general sound fields because any sound field can be expressed as the superposition of plane waves. For a general but single frequency sound field, which can be written as \( p_h(x_h,y_h,z_H;i) = P_0 e^{ik_{h0}x_0} e^{-i2\pi f_{h0}t} \), the measured signal can be expressed as

\[
p_m(0,y_m,z_H;i) = p_h(S_{m,h}(t),y_h,z_H;i)
\]

\[
= P_0 e^{ik_{h0}x_0} e^{-i2\pi f_{h0}t},
\]

Notice that the hologram \( (P_h) \) can be reconstructed from the complex envelope of the measured signal.

When a sound field has a continuous band-limited spec-
the previous result can also be applied. We can express the spectrum in terms of the center frequency and bandwidth, which are denoted by \( f_{hc} \) and \( B \) (see Fig. 3). Then, the sound field can be expressed as

\[
p_h(x_h, y_h, z_H; t) = \int_{f_{hc} - B/2}^{f_{hc} + B/2} P_h(x_h, y_h, z_H; f_h) e^{-i2\pi f_h t} df_h,
\]

where \( f_{hc} = f_{hc} - B/2 \) and \( f_{hc} = f_{hc} + B/2 \). Notice that we must apply a filter to obtain this signal in practice. If the band-limited sound field is produced by coherent sources and the bandwidth is narrow, then the sound field can be expressed as

\[
p_h(x_h, y_h, z_H; f_h) = A(f_h) P_{hc}(x_h, y_h, z_H; f_h)
\]

\[
(f_{hc} - B/2 \leq f_h \leq f_{hc} + B/2),
\]

where \( A(f_h) \) is the normalized source spectrum, which is defined as the ratio of a complex amplitude of sound field at \( f_h \) in the band to that of center frequency [see Fig. 3(b)]. Then Eq. (6) can be written as

\[
p_h(x_h, y_h, z_H; t) = P_{hc}(x_h, y_h, z_H; f_{hc}) \int_{f_{hc} - B/2}^{f_{hc} + B/2} A(f_h) e^{-i2\pi f_h t} df_h.
\]

The normalized source spectrum must be obtained from measurements. A reference microphone, fixed to noise sources at \((x_{ref}, y_{ref}, z_{ref})\), provides

\[
A(f_h) = P_{ref}(x_{ref}, y_{ref}, z_{ref}; f_h)/P_{ref,c}(x_{ref}, y_{ref}, z_{ref}; f_{hc}),
\]

where \( P_{ref}(x_{ref}, y_{ref}, z_{ref}; f_h) \) and \( P_{ref,c}(x_{ref}, y_{ref}, z_{ref}; f_{hc}) \) represent the reference microphone spectrum of an arbitrary frequency \( f_h \) and that of center frequency \( f_{hc} \). Notice that

\[
P_{ref,c}(x_{ref}, y_{ref}, z_{ref}; f_{hc}) = \text{constant}.
\]

This equation states that a coherent narrow band sound field can be modeled as the product of the representative sound field (spatial information) and the normalized source signal (temporal information). Then the previous procedure [Eqs. (4) and (5)] can also be applied to the coherent narrow band sound field. The measured pressure by the line array can be written as

\[
p_m(x_{ref}, y_{ref}, z_{ref}; t) = P_{hc}(x_{ref}, y_{ref}, z_{ref}; f_{hc}) P_{ref,c}(x_{ref}, y_{ref}, z_{ref}; f_{hc}).
\]

The representative hologram \( P_{hc}(x_{ref}, y_{ref}, z_{ref}; f_{hc}) \) of the narrow band sound field can be obtained if we measure the complex signal of the reference microphone \( P_{ref,c}(x_{ref}, y_{ref}, z_{ref}; f_{hc}) \) simultaneously. Figure 4 clearly demonstrates this concept in frequency domain; MFAH for a coherent narrow band noise [Eq. (11)] is compared with that of sinusoidal one [Eq. (5)].

Moving frame acoustic holography cannot directly be applied to the visualization of general transient noise sources because the spatial distribution of sound pressure on the hologram coordinate varies with respect to time. Strictly speaking, a plane array has the ability to obtain a general transient.
holo-gram. The speed change of the vehicle during the pass-by test makes the sound field generated by a rolling tire transient as well. However, if the speed change is negligible during the period of our interest, then the sound field can be assumed to be stationary. We call the sound field of this kind quasistationary in time. In practice, this assumption can be made because MFAH uses the time signal less than 0.5 second in length for the visualization of pass-by noise. The speed and frequency changes are small enough to be neglected in this period of time (this will be illustrated in the next section). Then, the quasistationary sound field can be modeled as the product of a representative hologram and the source signal. This allows us to apply MFAH to the visualization of pass-by noise.

The above can be extended to a general transient noise source that can be regarded as piecewise quasistationary. We divide the measured signal by a line array into the series of time signal. This is readily done by introducing time window \( w_n \), that is,

\[
p_h(S_{m/h}(t), y_h, z_H; t) = \sum_{n=1}^{N} p_h^{(n)}(S_{m/h}(t), y_h, z_H; t_{n-1} \leq t \leq t_n),
\]

where \( p_h^{(n)}(S_{m/h}(t), y_h, z_H; t_{n-1} \leq t \leq t_n) = p_h(S_{m/h}(t), y_h, z_H; t_{n-1} \leq t) w_n(t_{n-1}) \) is the \( n \)th Doppler shifted signal to which MFAH can directly be applied (Fig. 5). We denote the hologram of the \( n \)th Doppler shifted signal by \( P_h^{(n)}(x_h^{(n-1)} \leq x_h \leq x_h^{(n)}, y_h, z_H; f_h^{(n)}) \), where \( x_h^{(n)} = S_{m/h}(t_{n-1}) \) and \( x_h^{(n)} = S_{m/h}(t_n) \). The frequency \( f_h^{(n)} \) denotes the frequency of reference signal corresponding to the \( n \)th Doppler shifted one. Then, the hologram can be readily obtained by employing Eq. (11). After obtaining the \( N \) holograms, a representative hologram of the transient source can be obtained by adding the holograms, that is,

\[
P_h(x_h, y_h, z_H) = \sum_{n=1}^{N} P_h^{(n)}(x_h^{(n-1)} \leq x_h \leq x_h^{(n)}, y_h, z_H; f_h^{(n)}).
\]

The windowed time signal reduces not only frequency resolution of the signal but also wave number resolution of the hologram. In extreme case, if the window is very short, we cannot distinguish the frequency components of our interest from other ones. Notice that the spatial resolution of this hologram is the same as what would be obtained if no time window were used to the measured time signal. It can be determined by the product of the relative velocity and the sampling period.

**B. Reconstructed magnitude and the method of correction**

In this section, the reconstructed magnitude by MFAH is analyzed. For a single frequency sound field, it is clear that MFAH provides the exact magnitude of the reconstructed hologram. Equations (4) and (5) illustrate this.

However, MFAH cannot provide the exact magnitude of a narrow band sound field because it reconstructs a hologram (representative hologram) of the sound field based on the model [Eq. (8)]. From Eq. (11), the magnitude of reconstructed sound field can be denoted by \( |P_{h,B}| = |P_h(x_h, y_h, z_H; f_h)| \), which is the magnitude of the representative hologram at the center frequency. The true magnitude of hologram \( |P_{h,B}^{(true)}| \) of a narrow band sound field can be defined as

\[
|P_{h,B}^{(true)}| = \left\langle |P_h(x_h, y_h, z_H; t)| \right\rangle_{av} = \sqrt{\lim_{T \to \infty} \frac{1}{T^2} \int_{-T/2}^{T/2} |P_h^2(x_h, y_h, z_H; t)| dt},
\]

where \( \langle \cdot \rangle_{av} \) means time average. The time average of \( P_h^2 \) can be written by using Parseval theorem,

\[
\lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} P_h^2(x_h, y_h, z_H; t) dt = \frac{1}{T} \int_{f_{h_{B}}}^{f_{h_{B}+\Delta f_h}} \frac{P_h^2(x_h, y_h, z_H; f)}{df_h} df_h = \frac{1}{T} \int_{f_{h_{B}}}^{f_{h_{B}+\Delta f_h}} \frac{P_h^2(x_h, y_h, z_H; f) df_h}{df_h},
\]

where \( P_h^2 \) denotes the spectral density. In discrete domain, \( 1/T \) will be the spectral resolution \( \Delta f_h \) (that is, \( 1/T = \Delta f_h \)) and \( f_{h_{B}} = k \Delta f_h \) (if \( k \) is integer). Therefore, Eqs. (14) and (15) can be written as

\[
|P_{h,B}^{(true)}| = \sqrt{\sum_{k} |P_h^2(x_h, y_h, z_H; k \Delta f_h)(\Delta f_h)^2|},
\]

where \( P_{h,k}(x_h, y_h, z_H; k \Delta f_h) = P_h(x_h, y_h, z_H; k \Delta f_h \Delta f_h) \). Therefore the correction factor (\( \alpha \)), which can be defined as \( |P_{h,B}^{(true)}| \alpha = |P_{h,B}^{(true)}| \), to correct the reconstructed magnitude is...
\[
\alpha = \frac{P_{h,B}^{\text{true}}}{P_{h,B}} = \sqrt{\sum_k |P_{h,k}(x_h, y_h, z_h; k\Delta f_h)|^2 / |P_{h,c}(x_h, y_h, z_h; f_{hc})|^2}.
\]

In practice, the correction factor has to be obtained from the reference microphone signal,

\[
a_{\text{ref}} = \sqrt{\sum_k |P_{\text{ref},k}(x_{\text{ref}}, y_{\text{ref}}, z_{\text{ref}}; k\Delta f_{\text{h}})|^2 / |P_{\text{ref,c}}(x_{\text{ref}}, y_{\text{ref}}, z_{\text{ref}}; f_{hc})|^2}.
\]

When the sound field is a coherent narrow band one, this can be used instead of Eq. (17), that is

\[
a = a_{\text{ref}}.
\]

The proof of Eq. (19) is presented in Appendix A.

III. EXPERIMENTAL RESULTS

A. Experimental setup

In order to verify the applicability of moving frame acoustic holography to pass-by noise, a set of complicated but well controlled experiment was performed. Figure 7 illustrates experimental setup. The vertical line array of 16 microphones was used to measure the Doppler shifted signal. The microphone spacing was 0.1 m so that spatial aliasing below 1 kHz can be avoided. The time signal was recorded by using a multichannel signal analyzer that can sample 32 channels simultaneously. For verification purpose, a loudspeaker unit was used to produce a controlled sound. We attached it to the right side of the vehicle.

We made special tread pattern tires that radiate narrow band noise. Two vehicles were used. One was specially de-
signed for reducing noises from the vehicle so that they would not affect the controlled sound from the loudspeaker unit and noise from the special tread pattern tires. The other was a normal one that is used for visualizing the engine noise. A tire RPM signal, which produces one period of square wave per one revolution of tire, was recorded. Running distance per one revolution of tire could be calculated by measuring time interval for vehicle to move 10 m at constant speed. Two photoelectric sensors, separated by 10 m, were used in order to measure the time interval. The tire RPM signal and two photoelectric sensors enable us to obtain the relative position between the moving vehicle and the vertical line array. They provide the relative coordinate transformation [Eq. (2)] that transforms measured signal into the pressure on the hologram coordinate.

In the case of the loudspeaker experiment, a reference microphone was installed near the loudspeaker unit to measure the source signal (or, normalized source spectrum). In the case of tire noise visualization, we installed two reference microphones near the front and rear tires (Fig. 7) to improve the observability (to avoid measuring a weak sound at the reference microphone). It is noteworthy that the proposed method requires only one reference microphone if the noise source under study emits a tonal or coherent narrow band noise. A digital audio tape (DAT) recorder was used to record

FIG. 8. Validation of MFAH for pass-by noise. A loud speaker radiates a pure tone signal varying from 520 Hz to 530 Hz. (a) Spectrogram of reference microphone signal. Dashed lines denote the period of our interest. The period is about 0.4 second. (b) Predicted sound field on a source plane. (c) Verified result for pure tone.

FIG. 9. Comparison between the results by STSF and MFAH. (a) Predicted sound field on a tire surface by STSF. This can be regarded as a true value. (b) Predicted sound field on a tire surface by MFAH ("O" denotes a microphone).

FIG. 10. Tread pattern of the special tread pattern tire.
the reference microphone signals and the tire RPM signal. The reference microphones and the DAT recorder were installed inside the vehicle. Note that signals from the reference microphones and the array microphones must be sampled simultaneously; one synchronization signal generator and two receivers were used. The received signals were recorded by both the DAT recorder and the signal analyzer during the measurement. They allowed us to synchronize the reference and the array signals.

B. Validation of MFAH

The applicability of MFAH to moving noise sources at constant speed was verified in Ref. 20. When the vehicle accelerates according to the method of pass-by noise measurement (ISO 362), the applicability of MFAH can be verified by the following loudspeaker experiment. A loudspeaker unit attached to an accelerating vehicle radiates a sound field whose frequency varies from 520 Hz to 530 Hz [Fig. 8(a)]. Figure 8(a) shows the spectrogram of radiated sound that can be obtained from the reference microphone. Figure 8(b) shows the predicted pressure field on the source plane. Figure 8(c) shows the verified result. The verified result can be obtained when the loudspeaker unit (it radiates a 450 Hz sound field) moves with constant velocity (55 km/h). The results show a good agreement. They validate the applicability of the proposed method to pass-by noise. It is noteworthy that the sound field can be regarded as a quasistationary when the frequency change is small (about 10 Hz) during the measurement.

The applicability of MFAH to the tire noise was also verified by comparing with STSF (spatial transformation of sound fields) system, 23 which is commercial software for acoustical holographic prediction based on the step-by-step measurement. We assume that the result by the STSF system is true. Notice the STSF method uses much more information than the proposed method. The special tread pattern tire was installed to a dynamometer in a semianechoic chamber. It ran

![Figure 8](image_url)

**Figure 8**

(a) Spectrogram of radiated sound that can be obtained from the reference microphone. (b) Predicted pressure field on the source plane. (c) Verified result. (d) Relative position of the line array on the hologram coordinate with respect to time. Speed change is also negligible during measurement period.
at 50 km/h on the dynamometer. It radiates a narrow band noise whose center frequency is 460 Hz and 10 Hz bandwidth. In STSF method, three reference microphones were used. This enables us to identify three independent noise sources. We measured 17×14 points by using a line array that has seven microphones. A step-by-step scanning method was employed in STSF method. The microphone spacing was 6 cm. The distance between the tire surface and the hologram was 10 cm. Figure 9 shows the predicted pressure field on the assumed tire surface by STSF method. Very similar sound fields can be observed from the result obtained by MFAH [Fig. 9(b)]. We used a line array of nine microphones. The microphone positioning system (B&K type 9665) was used to sweep the sound field. The result shows a good agreement with that by STSF (true value). Both results show that the leading edge of tire is a dominant noise source. This verified the use of MFAH to the noise generated by the special tread pattern tire. Figure 9 also implies that the noise source of the special tread pattern tire can be regarded as a coherent band-limited one.

C. Visualization of pass-by noise on a moving vehicle

We used the special tread pattern tire to visualize the tire noise generated by the pass-by test. The tire was designed to generate narrow band noise whose center frequency and bandwidth are 500 Hz and 10 Hz at 55 km/h. This enables us to see the effect of driving condition. The tread pattern of tire is shown in Fig. 10. We installed the special tread pattern tire on the right side of the vehicle (the surface of visualization). Two smooth tires, which do not have tread pattern, were installed on the other side.

Figure 11 shows spectrograms of the reference microphone according to running condition. Frequency of the tire remains constant when the vehicle runs at constant speed (55 km/h) [Fig. 11(a)], compare with vertical dashed line]. When the vehicle accelerates from 50 km/h according to ISO 362, the frequency of tire noise increases about 10 Hz (from 470 Hz to 480 Hz) [Fig. 11(b)]. However, we cannot observe the frequency decrease of tire noise when the vehicle coasts down from 55 km/h [Fig. 11(c)]. Notice that the frequency variation is very small so that the tire noise can be assumed to be quasistationary. Figure 11(d) shows the relative position of array microphones on the hologram coordinate with respect to time. This illustrates that the change of vehicle speed during the period of our interest is small enough to be neglected. Figure 11 implies that the proposed method can be applied to the visualization of pass-by noise.

Figures 12–16 demonstrate the effect of driving condition on the radiation of tire noise. Figure 12 represents the pressure magnitude and the three dimensional active intensity on the assumed source plane (z_h=0) when the vehicle runs at constant velocity. (a) Sound pressure magnitude. (b) Active intensity.

FIG. 12. The special tread pattern tire noise distribution on the assumed source plane (the surface of the vehicle, z_h=0) when the vehicle runs at constant velocity. (a) Sound pressure magnitude. (b) Active intensity.
FIG. 13. The animation of sound pressure during one period (T) of corresponding frequency is presented when the vehicle runs at constant velocity. The visualization plane is $z_h = 0$. Notice that the interference between the radiated noise from the front tire and that from the rear one results in the high pressure in the center of the vehicle.
FIG. 14. The special tread pattern tire noise distribution on the assumed source plane (the surface of the vehicle, \(z_h=0\)) when the vehicle is accelerated from 50 km/h. (a) Sound pressure magnitude. (b) Active intensity.

FIG. 15. The special tread pattern tire noise distribution on the assumed source plane (the surface of the vehicle, \(z_h=0\)) when the vehicle coasts down from 55 km/h. (a) Sound pressure magnitude. (b) Active intensity.
Figure 14(a) shows the direction of propagation of the radiated noise. The radiated sound from the front tire propagates in the forward direction. Figure 15 shows the result when the vehicle coasts down from 55 km/h. The result illustrates that the rear tire is dominant noise source. We can observe that the radiated sound varies significantly according to the driving condition of the vehicle. Figure 16 shows active intensity (x and z directional component) and sound pressure from the source to the pass-by noise measurement location. They are visualized on the $y_h=0.5$ m plane [Fig. 16(a)]. The results demonstrate how the radiated noise propagates in the far field.

Figures 17 and 18 illustrate the engine noise of a vehicle during pass-by test. The spectrogram of the noise is shown in Fig. 17(a). The frequency change is very small so that the proposed method can be applied. The radiated noise at the second and the third harmonic of firing frequency of engine (60 Hz) were visualized in Figs. 17(b) and (c). Notice that the rear seat is very noisy at the third harmonic of the firing frequency. The three dimensional active intensity distributions on the assumed source plane are visualized in Fig. 18.

IV. CONCLUSIONS

Tire and engine noise during pass-by test can be visualized by means of an improved moving frame acoustic holography (MFAH). We assumed that tire noise during pass-by test is quasistationary. The proposed method was verified by a loudspeaker experiment. The magnitude correction method was also proposed. A special tread pattern tires were made in order to visualize effects of driving condition. The driving condition significantly changes the radiation pattern. Sound intensity maps were also visualized from the source plane to the measurement position of the pass-by noise level (ISO 362).
FIG. 17. Engine noise distribution (sound pressure magnitude) on the assumed source plane (the surface of vehicle, $z_h = 0$). (a) Spectrogram of the engine noise. (b) Pressure distribution of the engine noise at 120 Hz. The bandwidth is 16 Hz. (c) Pressure distribution of the engine noise at 180 Hz. The bandwidth is 18 Hz.

FIG. 18. Engine noise distribution (active intensity) on the assumed source plane (the surface of vehicle, $z_h = 0$). (a) Active intensity distribution of the engine noise at 120 Hz. The bandwidth is 16 Hz. (b) Active intensity distribution of the engine noise at 180 Hz. The bandwidth is 18 Hz.
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APPENDIX: THE FEASIBILITY OF USING REFERENCE MICROPHONE FOR THE MAGNITUDE CORRECTION

Let us consider $N$ perfectly correlated noise sources that emit a coherent sound field. We denote the spectrum of the $n$th source located at $(x_{Sn}, y_{Sn}, z_{Sn})$ by $S_n(f_h)$ ($n = 1, 2, \ldots, N$). Since the sources are perfectly correlated the following relation must be satisfied:

$$S_n(f_h) = G_{n1}(f_h)S_1(f_h) \quad (n = 2, 3, \ldots, N), \quad (A1)$$

where the transfer function $G_{n1}(f_h)$ can be assumed to be constant $(G_{n1}(f_h) = G_{n1}^0)$ for narrow band signal. We denote the transfer function between the $n$th source signal and the signal at $(x_h, y_h, z_h)$ on the hologram as $H_n(R_n, f_h)$, where $R_n = \sqrt{(x_h - x_{Sn})^2 + (y_h - y_{Sn})^2 + (z_h - z_{Sn})^2}$ (see Fig. 19). When the source emits a narrow band noise, we can assume that $H_n(f_h)$ is independent of frequency. In this case, we denote $H_n(R_n, f_h) = H_n^0(R_n)$. Then, the pressure spectrum at a point on the hologram can be written as

$$P_{h,k}(x_h, y_h, z_h; k\Delta f_h) = \sum_n \left[ H_n^0(R_n)S_n(k\Delta f_h) \right]$$

$$= \sum_n H_n^0(R_n)S_n(k\Delta f_h), \quad (A2)$$

FIG. 19. $N$ perfectly correlated noise sources that emit a coherent sound field.

where $f_h = k\Delta f_h$ ($k$ is integer). At the center frequency ($f_h = f_{hc}$), we rewrite Eq. (A2) as

$$P_{hc}(x_h, y_h, z_h; f_{hc}) = \sum_n H_n^0(R_n)S_n(f_{hc})$$

$$= \sum_n H_n^0(R_n)S_n(f_{hc}), \quad (A3)$$

by using the notation previously used in Sec. II. Then, the correction factor defined by Eq. (17) can be expressed by means of Eqs. (A2) and (A3).

$$\alpha = \frac{\sum_k |P_{h,k}(x_h, y_h, z_h; k\Delta f_h)|^2}{|P_{hc}(x_h, y_h, z_h; f_{hc})|^2}$$

$$= \frac{\sum_k \left[ \sum_n H_n^0(R_n)G_{n1}^0S_1(k\Delta f_h) \right]^2}{\sum_n \left[ H_n^0(R_n)G_{n1}^0S_1(f_{hc}) \right]^2}$$

$$= \sqrt{\sum_k \left[ \sum_n H_n^0(R_n)G_{n1}^0 \right]^2 \left[ S_1(k\Delta f_h) \right]^2 / \sum_n \left[ H_n^0(R_n)G_{n1}^0 \right]^2 \left[ S_1(f_{hc}) \right]^2} = \sqrt{\sum_k \left[ S_1(k\Delta f_h) \right]^2 / \left[ S_1(f_{hc}) \right]^2}. \quad (A4)$$

This equation can also be obtained from the reference microphone spectrum when the noise sources radiate narrow band noise. We denote the transfer function between the $n$th source signal, $S_n(f_h)$, and the signal at a reference microphone $(x_{ref}, y_{ref}, z_{ref})$ as $T_n(r_n, f_h)$, where $r_n = \sqrt{(x_{ref} - x_{Sn})^2 + (y_{ref} - y_{Sn})^2 + (z_{ref} - z_{Sn})^2}$ (see Fig. 19 again). As previously mentioned, $T_n(r_n, f_h)$ is independent of frequency for narrow band noise, that is, $T_n(r_n, f_h) = T_n^0(r_n)$. The spectrum at the reference microphone can be written as

$$P_{ref,k}(x_{ref}, y_{ref}, z_{ref}; k\Delta f_h) = \sum_n T_n(r_n, k\Delta f_h)S_n(k\Delta f_h) = \sum_n T_n^0(r_n)S_n(k\Delta f_h). \quad (A5)$$

At the center frequency,

$$P_{ref}(x_{ref}, y_{ref}, z_{ref}; f_{hc}) = \sum_n T_n(r_n, f_{hc})S_n(f_{hc}) = \sum_n T_n^0(r_n)S_n(f_{hc}). \quad (A6)$$

From Eqs. (A5) and (A6), Eq. (18) can be expressed as
\[
\alpha_{\text{ref}} = \sqrt{\sum_{k} \left| P_{\text{ref},k}(x_{\text{ref}},y_{\text{ref}},z_{\text{ref}};k\Delta f_{\text{h}}) \right|^2 / \sum_{k} \left| P_{\text{ref},k}(x_{\text{ref}},y_{\text{ref}},z_{\text{ref}};k\Delta f_{\text{h}}) \right|^2}
\]

\[
= \sqrt{\sum_{n} \left| T_n^0(r_n)S_n(k\Delta f_{\text{h}}) \right|^2} / \sqrt{\sum_{n} \left| T_n^0(r_n)S_n(f_{\text{hc}}) \right|^2}.
\]

If we use \( S_n(f_{\text{hc}}) = G_{n1}^0S_1(f_{\text{hc}}) \), Eq. (A7) can be reduced to

\[
\alpha_{\text{ref}} = \sqrt{\sum_{n} \left| T_n^0(r_n)G_{n1}^0S_1(k\Delta f_{\text{h}}) \right|^2} / \sqrt{\sum_{n} \left| T_n^0(r_n)G_{n1}^0S_1(f_{\text{hc}}) \right|^2}.
\]

\[
= \sqrt{\sum_{n} \left| T_n^0(r_n)G_{n1}^0 \right|^2 \sum_{k} \left| S_1(k\Delta f_{\text{h}}) \right|^2} / \sqrt{\sum_{n} \left| T_n^0(r_n)G_{n1}^0 \right|^2 \left| S_1(f_{\text{hc}}) \right|^2} = \sqrt{\sum_{k} \left| S_1(k\Delta f_{\text{h}}) \right|^2 / \left| S_1(f_{\text{hc}}) \right|^2}.
\]

Therefore, we can prove Eq. (19) by comparing Eq. (A8) with Eq. (A4).


2SAEJ1470, “Measurement of noise emitted by accelerating highway vehicles.”


