VISUALIZATION OF NOISE GENERATED BY MOVING VEHICLES

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INTRODUCTION

Noise generated by moving vehicles has many different sources. For example, noise of conventional passenger cars can be emitted from various places such as tires, engine, exhaust pipe, transmission box, or other places. Not only for adequately preparing environmental regulation of vehicle noise but also for developing quieter car, having a method which gives how and where noise generated and propagates will be ultimate mean of noise abatement. Conventional visualization methods of noise generated by moving vehicles is hologram measurement by using planar array attached to a moving vehicle[1]. This requires complex measurement system and non-trivial investment.

In this paper, we attempt to achieve this goal by employing a line array of microphone which has 16 microphones. Basic idea is to construct two dimensional hologram which permits us to construct entire noise image in space and time based on this measurement. This enables one to see every details of sound field of interest, which include not only pressure but also particle velocity, acoustic power, and intensity.[2]

This measured sound pressure obviously contains necessary information about the noise from moving vehicle, but modulated (Doppler shifted). The method uses three coordinate systems; one is hologram coordinate which moves with vehicle. The other two are measurement and reference coordinate. The sound pressure from a moving vehicle is expressed in these three coordinate system. This provides the way to transfer or map the measured sound into the desired pressure on the hologram surface which is moving with vehicle.[3] The method can handle variable speed of vehicle.

Several field experiments were conducted and results are demonstrated in this paper. Noise image generated by motorcycle with respect to time are shown. Noise image from a passenger car are also demonstrated. The results demonstrates that we can see where noise comes and how it propagates.

THEORETICAL FORMULATION

Sound pressure expression in three coordinate systems

The theoretical formulation starts with introducing the three coordinate systems which is depicted in Fig. 1. The first is reference coordinate which is fixed in space. The second is measurement coordinate which is allowed to move. The third is hologram coordinate which can either move or be stationary depending on whether noise source is moving or not. This is the coordinate system where one obtains hologram. It can be used to predict all acoustic variables

on any planes.
Sound pressure on each coordinate system can be expressed as follows. $p(x, y, z; t)$ represents sound pressure in reference coordinate, $p_h(x_h, y_h, z_h; t)$ in hologram coordinate which moves with noise source, and $p_m(x_m, y_m, z_m; t)$ in measurement coordinate. The general coordinate transformations between this coordinate system are

$$\vec{x} = \vec{S}_m(t) + \vec{x}_m, \quad \vec{x} = \vec{S}_h(t) + \vec{x}_h. \tag{1}$$

where, $\vec{S}_m(t)$ represents relative displacement between origin of reference coordinate and origin of measurement coordinate. $\vec{S}_h(t)$ represents relative displacement between origin of reference coordinate and origin of hologram coordinate similarly. Without loss of generality, one assumes that three coordinate are same location at t=0; $\vec{S}_m(0) = 0$ and $\vec{S}_h(0) = 0$ and they move in x direction. One denotes the relative displacement between origin of hologram coordinate and origin of measurement coordinate as $\vec{S}(t) = \vec{S}_m(t) - \vec{S}_h(t) = (S(t), 0, 0)$, then one obtains the following coordinate transformation.

$$x_h = S(t) + x_m, \quad y_h = y_m \quad , z_h = z_m \tag{2}$$

The relation between the measured sound pressure at the microphone array which is fixed at $x_m = 0$ (See Fig. 1) and sound pressure in hologram coordinate is

$$p_m(0, y_m, z_H; t) = p_h(S(t), y_h, z_H; t) \tag{3}$$

where, $x_h = S(t)$ and this equation essentially allows us to construct hologram in hologram coordinate when single valued inverse function $t = S^{-1}(x_h)$ exists. This means that temporal information must be uniquely transformed into spatial information.

Construction of hologram

Hologram is the sound pressure distribution on the hologram plane with respect to frequency. The pressure distribution in frequency domain is expressed by using temporal Fourier transform.

$$P_h(x_h, y_h, z_H; f_h) = F_T\{p_h(x_h, y_h, z_H; t)\} = \int_{-\infty}^{\infty} p_h(x_h, y_h, z_H; t) e^{i2\pi f_h t} dt \tag{4}$$

where, f_h represents observed frequency in hologram coordinate. When noise source moves with hologram coordinate, the observed frequency f in measurement coordinate is different to f_h due to Doppler effect. Instead of using (4), we use temporal Fourier transform of (3) to obtain hologram in hologram coordinate.

$$\begin{aligned} F_T\{p_m(0, y_m, z_H; t)\} &= \int_{-\infty}^{\infty} p_h(S(t), y_h, z_H; t) e^{i2\pi f t} dt \\ &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P_h(S(t), y_h, z_H; f_h) e^{-i2\pi f_h t} df_h e^{i2\pi f t} dt \end{aligned} \tag{5}$$

Our main objective is to obtain hologram which is the integrand in the Eq. (5). To achieve this goal, one can utilize inverse spatial Fourier transform with respect to x,

$$P_h(x_h, y_h, z_H; f_h) = F_X^{-1}\{\tilde{P}_h(k_x, y_h, z_H; f_h)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{P}_h(k_x, y_h, z_H; f_h) e^{ik_x x_h} dk_x \qquad (6)$$

Using Eq. (6) one can rewrite Eq. (5) as

$$F_T\{p_m(0, y_m, z_H; t)\} = \frac{1}{x_h / S^{-1}(x_h)} \int_{-\infty}^{\infty} \tilde{P}_h\left(\frac{2\pi(f_h - f)}{x_h / S^{-1}(x_h)}, y_h, z_H; f_h\right) df_h\ . \qquad (7)$$

The relation between the wave number (k_x) and the Doppler shifted frequency is

$$k_x = \frac{2\pi(f_h - f)}{x_h / S^{-1}(x_h)}. \qquad (8)$$

Eqs. (7) and (8) essentially state that the temporal Fourier transform of measured sound pressure is superposition of wave number(k_x) spectra centered at f_h's which are frequencies of interest in hologram coordinate. One can obtain hologram of f_h by filtering this Doppler shifted spectrum around f_h using band pass filter and taking inverse spatial Fourier transform. Fig. 2 depicts the hologram construction procedure for single frequency sound field. The result also holds when the relative velocity(u) between the measurement coordinate and the hologram coordinate is constant.[3] In this case, the following relations are used; $S(t) = ut$ and $x_h / S^{-1}(x_h) = u$.

The essential feature of this method imposes inherent limitation on constructing hologram. This is due to the effect of spreading frequencies around f_h. This phenomena are inherent when there is relative motion between the vehicle(or hologram) and the line array of microphone. When there is neighboring frequency($f_{h,n+1}$) around frequency of interest($f_{h,n}$), one has an overlap problem. This means that one would not be able to decompose the spread components of $f_{h,n}$ from those of $f_{h,n+1}$. The criteria to avoid this rather undesirable effect is addressed in reference [3] in detail for coordinate system with constant speed. When two frequencies of interest satisfy $f_{h,n+1} > f_{h,n}$, condition to avoid side band overlapping is

$$f_{h,n+1} > \frac{1+2M}{1-2M} f_{h,n}, \qquad M = \max\left(\frac{x_h / S^{-1}(x_h)}{c}\right) \qquad (9)$$

where, c is speed of sound. This is quite acceptable requirement in practice.

EXPERIMENTAL RESULTS

Several field experiments were performed to verify this method. Fig. 4 depicts experimental set-up to measure the hologram of moving vehicle. Fixed vertical line array of 16 microphones were used. We used one loudspeaker at right front window of the vehicle as depicted in Fig. 5. This result shows that our method not only visualizes the radiated sound field accurately but also locates the accurate source position. Fig. 6 shows noise image from moving motorcycle due to engine. Fig. 7 illustrates motion pictures of this noise image in space and time. We can see where noise comes and how it propagates from this result.

CONCLUSIONS

A new hologram measurement method to visualize noise generated by moving vehicles was discussed. Several field experiments are conducted and the results are demonstrated. This method proved to be very useful to measure hologram of moving source. This method can handle not only moving vehicle with constant speed but also moving vehicle with variable speed.

REFERENCES

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3. "Moving frame technique for planar acoustic holograph," H. -S. Kwon and Y. -H. Kim, *submitted to J. Acoust. Soc. Am.* (1996)

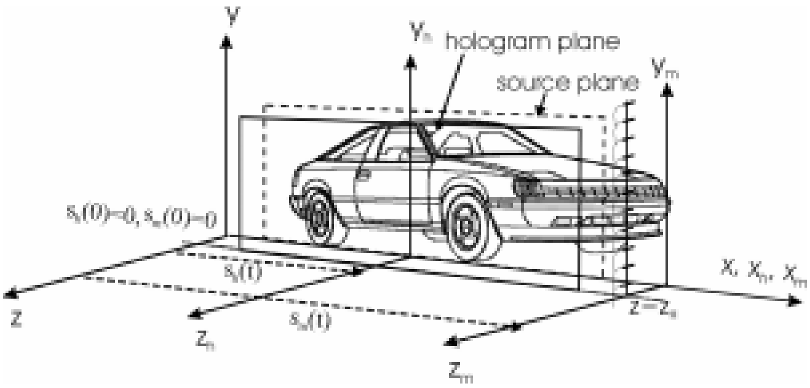


Fig. 1 Three coordinate systems(reference coordinate, hologram coordinate moves with vehicle and measurement coordinate). They are same location at t=0 and move in x direction.

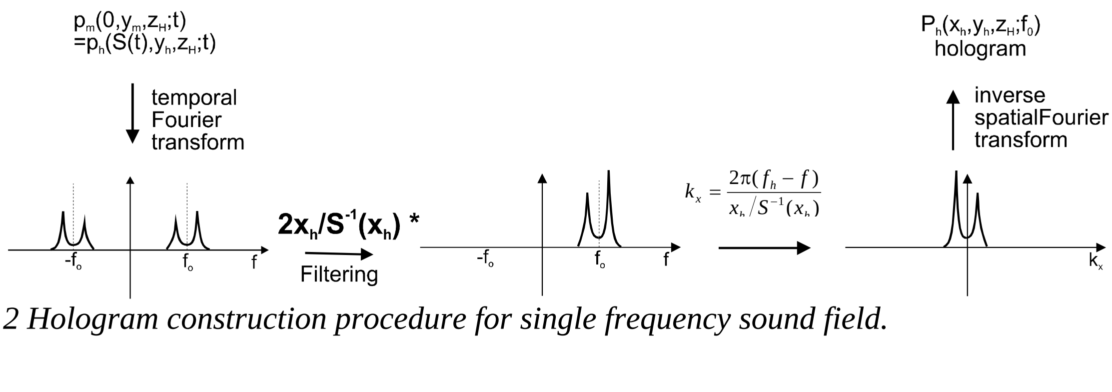


Fig. 2 Hologram construction procedure for single frequency sound field.

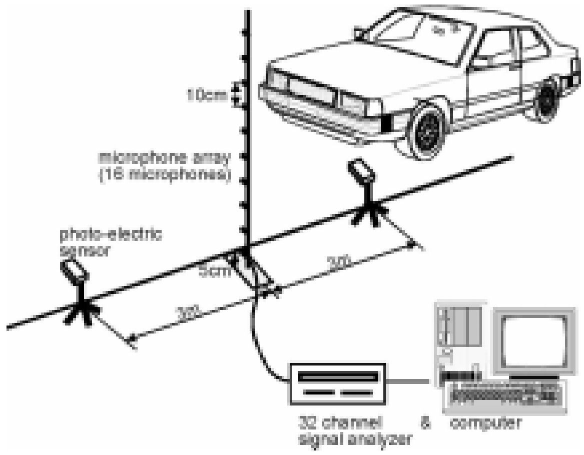
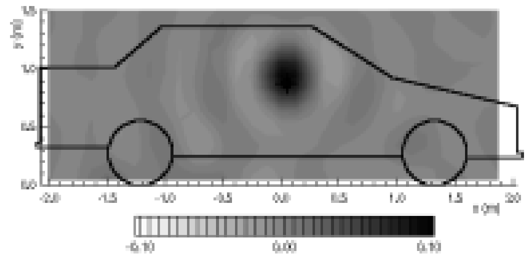
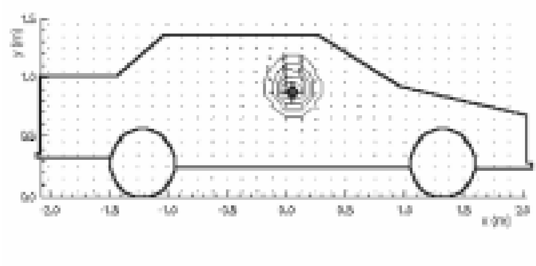


Fig. 3 Experimental set-up to measure hologram of moving vehicle. Fixed vertical line array of 16 microphones were used. Two photo-electric sensors were used to measure the constant speed of moving vehicle. For hologram data acquisition, 32 channel FFT signal analyzer and PC were used.

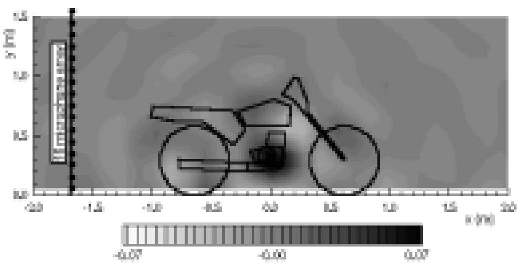


(a) predicted sound pressure map on the source plane

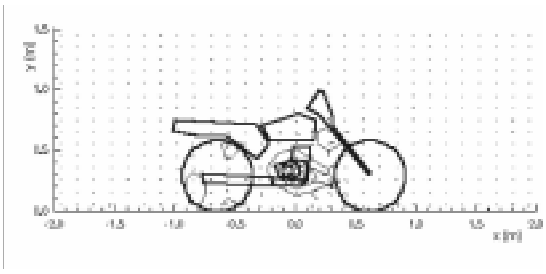


(b) predicted mean active intensity map on the source plane

Fig. 5 Predicted noise images of moving automobile experiment by using a loudspeaker at the front window. It radiates the 700Hz single frequency sound field. The automobile moves at the speed of 8.204m/s on the paved road, 62cm away from the array of microphone.

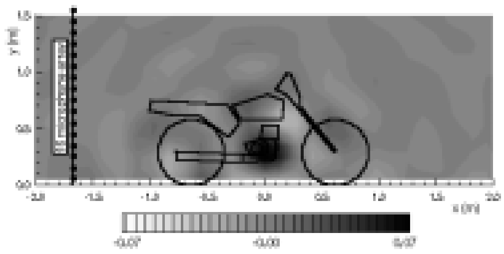


(a) predicted sound pressure map on the source plane

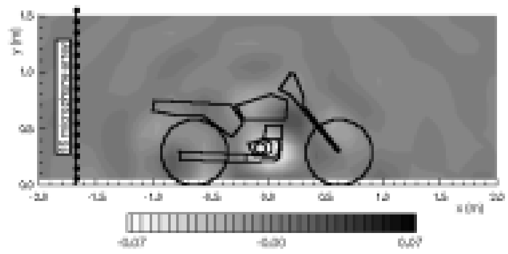


(b) predicted mean active intensity map on the source plane

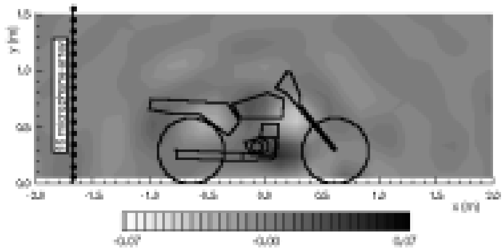
Fig. 6 Predicted noise images of moving motorcycle at 807Hz. The main noise source at this frequency is engine. The motorcyle moves at the speed of 8.901m/s on the paved road, 43cm away from the array of microphone.



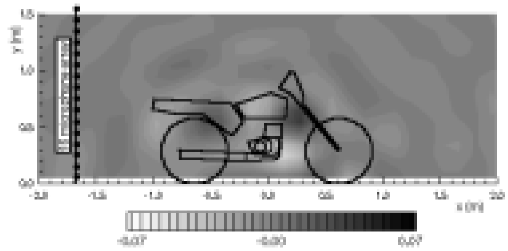
$2\pi ft = 0$



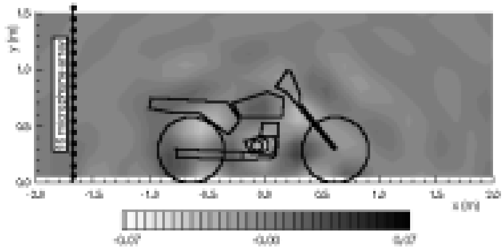
$2\pi ft = \pi$



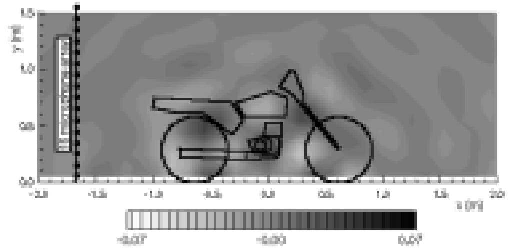
$2\pi ft = \pi/4$



$2\pi ft = 5\pi/4$



$2\pi ft = \pi/2$



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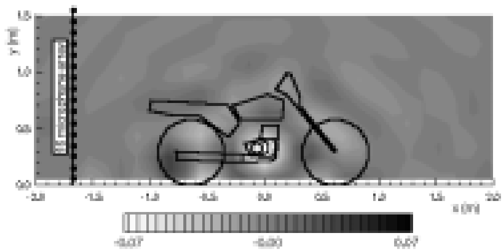

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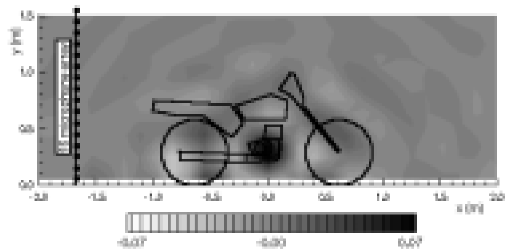

$2\pi ft = 7\pi/4$

Fig. 7 Animated noise image of moving motorcycle at 807Hz with respect to time. The motorcyle moves at the speed of 8.901m/s on the paved road, 43cm away from the array of microphone.