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MOVING NOISE SOURCE VISUALIZATION: ITS OVERVIEW AND EXAMPLES

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ABSTRACT

This paper introduces the method that can visualize the noise sources of a moving vehicle. The well-known problem definition associated with the method has two kinds. One is to enlarge the hologram so that we have better resolution. Another one is what is related with de-Dopplerization. The moving frame acoustic holography (MFAH) has been proved that it can be applied to the moving noise source of which generates narrow band noise. In fact, if the bandwidth is within 20 % of center frequency, it is found that the method is still applicable. This paper also shows that the technique is one of tries to use a mapping function, as generally used in inverse problem.

1 - INTRODUCTION

Acoustic holography requires sound pressure data on a hologram. Therefore we need to devise a microphone system which covers a plane of a hologram. The sound pressures on the hologram are to be measured by microphones, which are usually equidistantly spaced on the plane. The distance determines the sampling space, therefore provides sampling wave number. And the size of the plane, the horizontal and vertical length of the plane, decides the wave number resolution. Therefore the more number of microphone will give the better quality of acoustic holography. A simple consequence of which we can easily envisage from these primary properties of the acoustic holography is that we have to increase aperture size, in other words, enlarge the hologram size. There have been various attempts to achieve this objective. One of them is to virtually increase the size. This method essentially extrapolates the measured data so that eventually increases the size. As we can see, without any difficulty, this method assumes a kind of smooth change of sound pressure, the data, outside of the aperture, therefore unable to cope with somewhat rapid change of sound pressure outside the hologram. Other method would be the one of which actually increases the aperture size: not virtually increases, but really does. The moving frame acoustic holography [1,2] is of this kind. This method suggests to scanning an array microphone over the surface of interest, which can be a hologram. The aperture size therefore can be enlarged as much as we want. However, it is limited to be applied to the sound field of which is stationary with respect to the coordinate system attached to the sound source. The measurement coordinate of which actually carries the array microphone system has relative velocity with respect to the fixed coordinate. It is able to transform the signal obtained by the moving coordinate system to the coordinate affixed to the noise source. One of valuable advantages of this method is that it can envisage all acoustic variables of which produced by moving vehicle: acoustic pressure, intensity, and energy. This paper briefly reviews the sound visualization method, including Near Field Acoustic Holography [3], array antenna method [4-10], and introduces Moving Frame Acoustic Holography [1,2]. Various examples, including noise from automobile and tire noise, are shown.

2 - OBJECTIVE AND PROBLEM DEFINITION

The objective of visualizing the moving noise source is to find an appropriate mapping, which transfers measured variables to the ones that help us to understand noise source or sources. The visible ones are usually the best means to understand the spatial as well as time varying characteristics of the source. One of very commonly measured variables is acoustic pressure signal. Fig. 1 well illustrates the problem

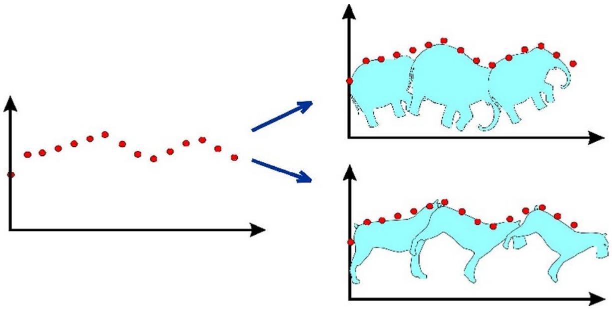


Figure 1: Possible mappings of a graph by means of "elephant" and "dog" as the basis function [11].

definition and objective we have. As we can see from Fig. 1, what we attempt to do is to map, or predict what is not measured, only based on the incomplete knowledge. There could be many possible mappings, which share the same measured data, as illustrated in Fig. 1.

Beam forming method maps the noise source by trying to find the locations that give maximum beam forming power. In this case, the mapping function is

$$P = w^H R w,\ \text{where}\ w = \frac{1}{\sqrt{M}} \left[\ e^{-jkd_1 \cos\theta},\quad e^{-jkd_2 \cos\theta},\quad \cdots,\quad e^{-jkd_M \cos\theta}\ \right]^T \tag{1}$$

P and R represent the beamforming power and the correlation matrix of the measured signal. M is number of microphones, k is the wave number, and θ is an assumed direction of the plane wave. d_i (i = 1,2,...,M) denotes distance of i-th microphone with respect to a reference point. Eq. (1) essentially finds the best angle in the sense that maximizes the beam forming power. The candidate function or mapping function can be what is based on planer wave or spherical wave, depending on the field of interest. If it is in far field, then planer wave model is appropriate. If it is expected to be used in near field, then spherical wave model is more appropriate [4-6]. The methods use a line array. In other words, it uses only information of "the back line of elephant" in Fig. 1. The mapping function or candidate function in this case is "elephant" or "dog." One can see then immediately that the performance of the methods depends directly on the likelihood of the function to the sound field generated by the source or sources. Another candidate of the mapping is to use trigonometric function as the candidate to express the sound field. Acoustic holography essentially belongs to this category. However, direct application of acoustic holography to visualize the moving noise source is not straightforward and requires extensive cost. This is simply because we have to devise the hologram that is moving with the noise source, if one uses a conventional holography method. The method suggested in 1998 [1] measures the noise generated by a moving noise source by using an array microphone system affixed to the ground. This method essentially claims that there is a way to find the mapping function that can be used for the hologram moving with the noise source by just based on the information measured on the non-moving, fixed on the ground, line array microphone system. This is a kind of secondary mapping problem. In other words, we attempt to model a true mapping function based on incomplete information.

3 - BASIC THEORY OF THE MOVING FRAME ACOUSTIC HOLOGRAPHY [2,3]

In fact, the signal obtained by the microphone and that obtained by the microphone fixed in space but the noise source is moving, are different [12]. However, when travelling speed of the source is smaller than the speed of sound, then the two measurement configurations can be regarded as identical ones [12]. And the situation illustrated by Fig. 2 is relatively easier to understand than the former case. From this reason, we will use Fig. 2 to explain the basic concept of the moving frame acoustic holography. The signal can be written as

$$p_m\left(x_m = 0; t\right) = p_h\left(x_h = u_{m/h} t; t\right) = P_0 e^{ik_{x0} u_{m/h} t} e^{-i2\pi f_{h0} t} \tag{2}$$

where the microphone and the noise source are fixed to the measurement coordinate (denoted by subscript m) and the hologram coordinate (denoted by subscript h). The relative speed of the microphone is $u_{m/h}$. This equation clearly shows that we can obtain the hologram by measuring the relative displacement of microphone to the noise source ($x_h = u_{m/h} t$) and the frequency of sound field (f_{h0}). The hologram, which is the complex envelope of the measured signal in this case, can be obtained by multiplying the conjugate of $e^{-i2\pi f_{h0} t}$ by both sides of the equation. [2]

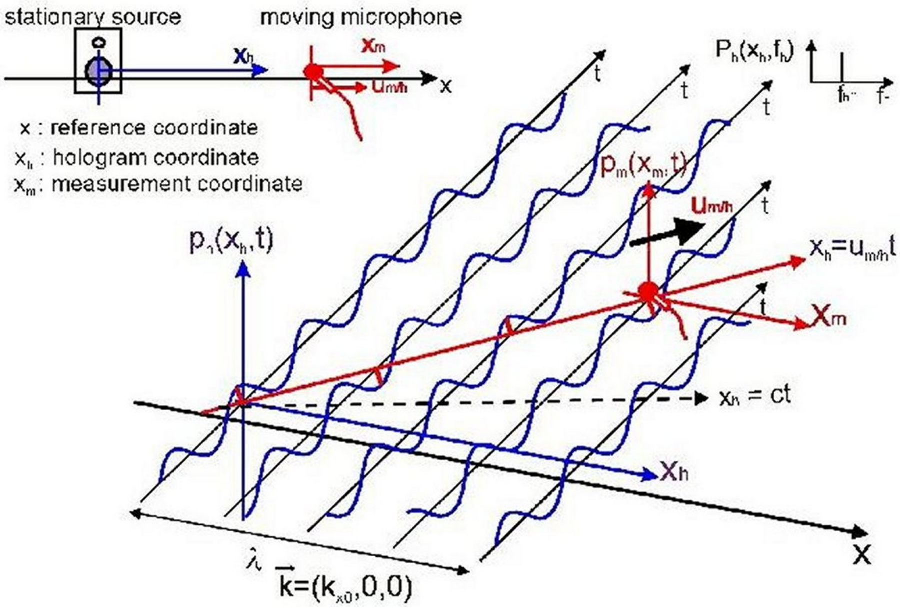


Figure 2: Basic concept of the moving frame acoustic holography.

Equation (2) can be regarded as a mapping function of moving frame acoustic holography because any sound field can be expressed as the infinite sum of plane waves. Notice that it is a sort of trigonometric function that has Doppler effect. Then, the general sound field measured by a moving microphone is expressed as the sum of equation (2). Reference [2] explains this concept in detail. For a general but single frequency sound field, which can be written as

$$p_h\left(x_h, y_h, z_H; t\right) = P_h\left(x_h, y_h, z_H; f_{h0}\right) \times e^{-i2\pi f_{h0}t}$$

the measured signal can be expressed as

$$p_m\left(x_m = 0, y_m, z_H; t\right) = p_h\left(x_h = u_{m/h}t, y_h, z_H; t\right) = P_h\left(x_h = u_{m/h}t, y_h, z_H; f_{h0}\right) \times e^{-i2\pi f_{h0}t} \quad (3)$$

As previously mentioned, the hologram (P_h) can be reconstructed from the complex envelope of the measured signal.

The moving frame acoustic holography can be extended to a band-limited noise. If the bandwidth of the noise is narrow with respect to a center frequency, the sound field can be expressed as the product of spatial and temporal information. In this case, equation (3) can be a mapping function for the band-limited sound field. Hologram can be reconstructed if we measure temporal information, that is, a source spectrum. See reference 2 for detailed explanation.

4 - EXTENSION OF THE MOVING FRAME ACOUSTIC HOLOGRAPHY TO PASS-BY NOISE VISUALIZATION [12]

The moving frame acoustic holography cannot directly be applied to the visualization of general transient noise sources. The speed change of the vehicle during pass-by test makes the noise generated by the vehicle transient. However, if we consider a sound field during a short period of time in which the speed change is negligible, then we can assume the sound field to be quasi-stationary. In practice, this assumption can be made because the moving frame acoustic holography 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 quasi-stationary sound field can be regarded as the product of a representative hologram and the source signal. This allows us to apply the moving frame acoustic holography to the visualization of pass-by noise.

This idea can be extended to a general transient noise source that can be regarded as piecewise quasi-stationary. We divide the measured signal by a line array into the series of time signal due to a quasi-stationary source signal. This is readily done by introducing time window w_n (Fig. 3). The windowed time signal reduces not only frequency resolution of the signal but also wave number resolution of the hologram. In the 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 any time window were not used to the measured time signal. It can be determined by the product of relative velocity and sampling period.

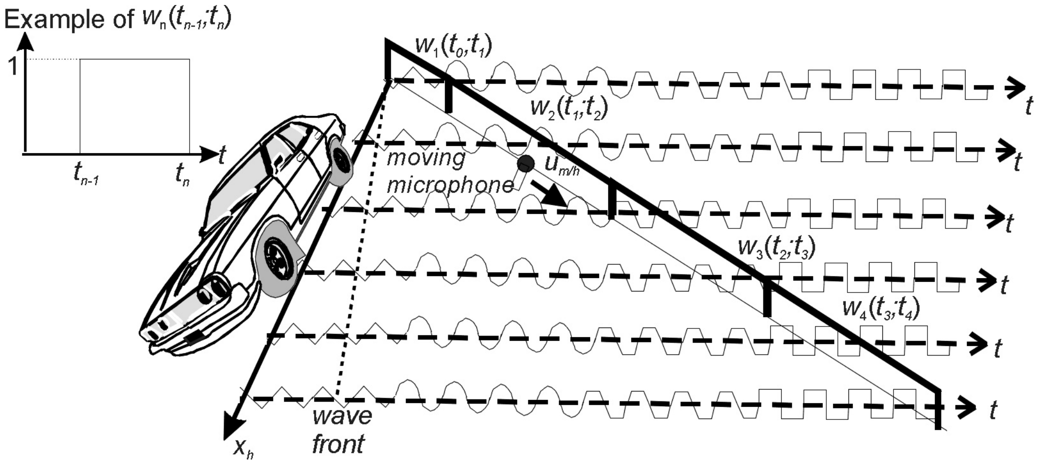
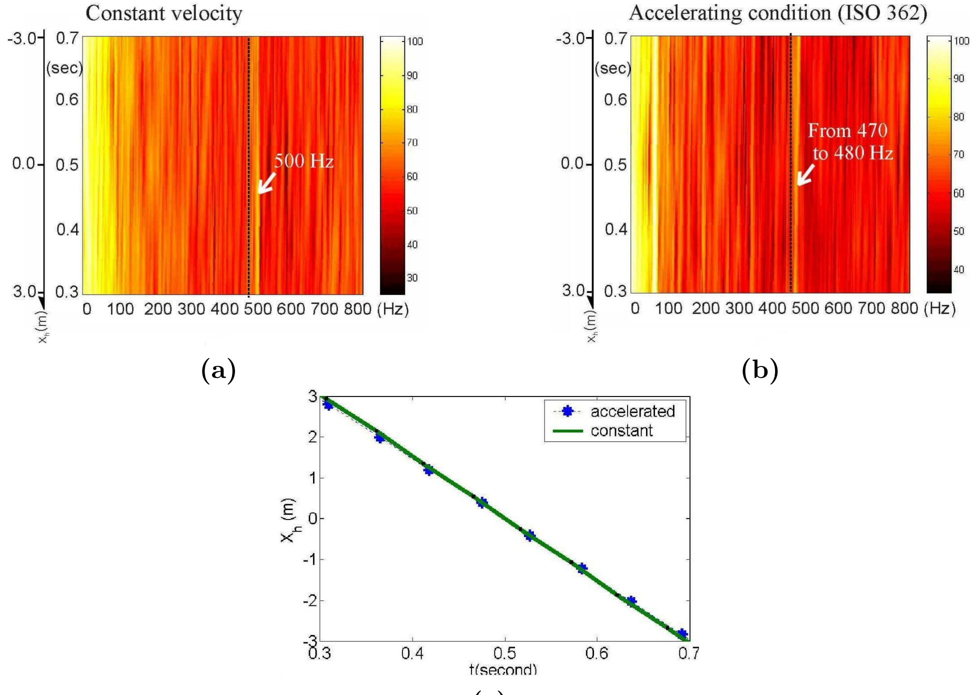


Figure 3: Concept of moving frame acoustic holography for pass-by noise.

5 - APPLICATION EXAMPLES

The noise generated by automobile and tire during pass-by test was visualized. We made a model tire that was designed to generate a narrow band noise. This enables us to see the effect of driving condition. Figure 4 shows spectrograms of tire noise according to running condition. Notice that the frequency variation is very small so that the tire noise can be assumed to be quasi-stationary. This is simply because the change of vehicle speed during the period of our interest is small enough to be neglected (Fig. 4c).



(a) **(b)**

(c)

Figure 4: Spectrograms of tire noise according to driving condition.

Figure 5 demonstrates the effect of driving condition on the radiation of tire noise. When the vehicle runs at constant speed (55. 25 km/h), both front and rear tires radiates sound. The radiated sound from the front tire interferes with that from the rear tire at the center of the vehicle. When the vehicle is accelerated from 50 km/h according to ISO 362, front tire radiates more sound than rear one does. We can observe that the radiated sound varies significantly according to the driving condition of the vehicle.

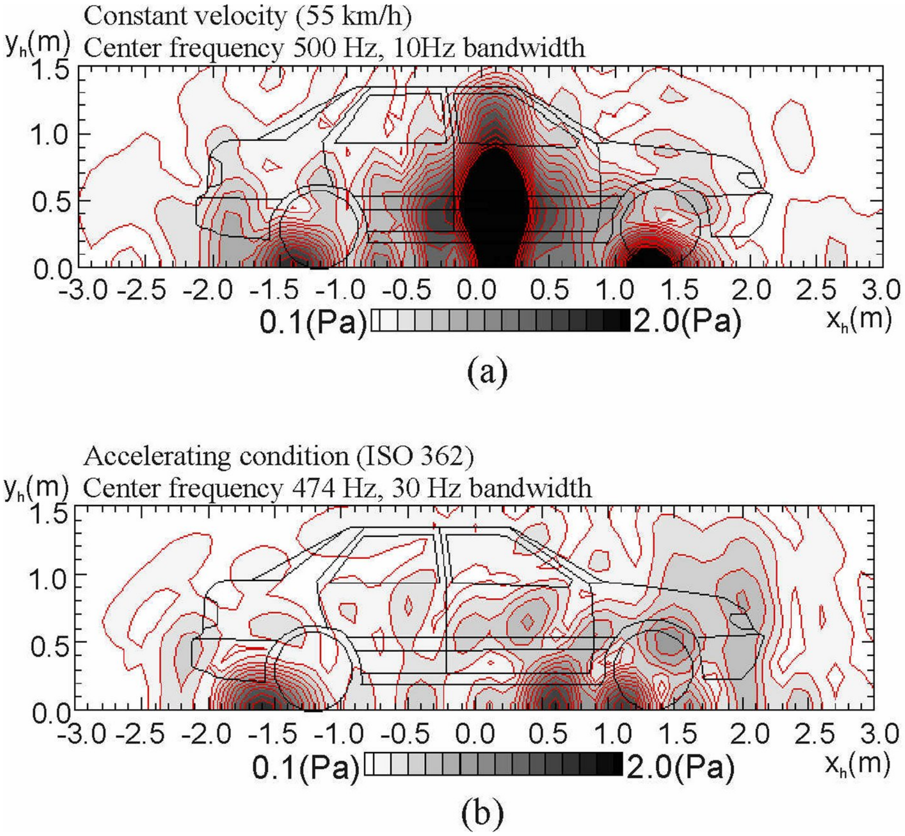


Figure 5: Visualization of the effect of driving condition.

Figure 6 illustrates the booming noise of a vehicle during pass-by test. The radiated noise at the second and the third harmonics of firing frequency of engine (60 Hz) were visualized. Notice that the rear seat is very noisy at the third harmonics of the firing frequency.

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REFERENCES

1. **H. -S. Kwon and Y. -H. Kim** , Moving frame technique for planar acoustic holography, *J. Acoust. Soc. Am.*, Vol. 103(4), pp. 1734-1742, 1998

2. **S. -H. Park and Y. -H. Kim**, An improved moving frame acoustic holography for coherent bandlimited noise, *J. Acoust. Soc. Am.*, Vol. 104(6), pp. 3179-3189, 1998

3. **J. D. Maynard, E. G. Williams and Y. Lee**, Nearfield acoustic holography: I. Theory of generalized holography and development of NAH, *J. Acoust. Soc. Am.*, Vol. 78(4), pp. 1395-1413, 1985

4. **D. H. Johnson and D. E. Dudgeon**, *Array signal processing: concepts and techniques*, Prentice-Hall, Englewood Cliffs, NJ07632, 1993

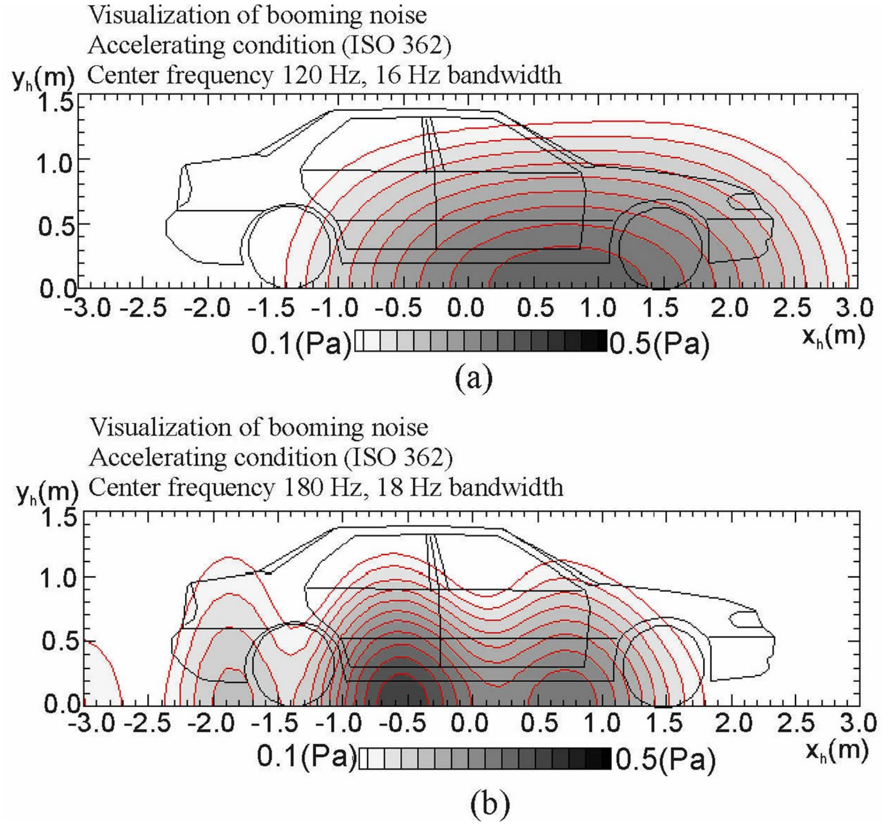

Figure 6: Visualization of booming noise.

5. **J. -W. Choi and Y. -H. Kim**, Spherical beamforming and MUSIC methods for estimation of location and strength of spherical sound sources, *Mech. Systems and Signal Proc.*, Vol. 9(5), pp. 569-588, 1995

6. **J. -W. Choi and Y. -H. Kim**, Estimation of locations and strengths of broadband planar and spherical noise sources using coherent signal subspace, *J. Acoust. Soc. Am.*, Vol. 98(4), pp. 2082-2093, 1995

7. **W. F. King III and D. Bechert**, On the sources of wayside noise generated by high-speed trains, *J. Sound Vib.* , Vol. 66(3), pp. 311-332, 1979

8. **B. Barsikow, W. F. King III, and E. Pfizenmaier** , Wheel/rail noise generated by a high-speed train investigated with a line array of microphones, *J. Sound Vib.*, Vol. 118(1), pp. 99-122, 1987

9. **Y. Takano, K. Terada, E. Aizawa, A. Iida, and H. Fujita**, Development of a 2-dimensional microphone array measurement system for noise sources of fast moving vehicles, In *Proceedings of Inter Noise 92*, pp. 1175-1178, 1992

10. **S. Bruhl and K. -P. Schmitz**, Noise source localization on highspeed trains using different array types, In *Proceedings of Inter Noise 93*, pp. 1311-1314, 1993

11. **J. K. Hammond**, Personal communication, June 1996.

12. **S. -H. Park and Y. -H. Kim**, Effects of the speed of moving noise sources on the sound visualization by means of moving frame acoustic holography (MFAH), *In review, J. Acoust. Soc. Am.*, 2000

13. **S. -H. Park and Y. -H. Kim**, Visualization of pass-by noise by means of moving frame acoustic holography, *Submitted to J. Acoust. Soc. Am.*, 2000