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Can We Hear the Shape of a Noise Source?

소음원의 모양을 들어서 상상할 수 있을까?[#]

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ABSTRACT

One of the subtle problems that make noise control difficult for engineers is "the invisibility of noise or sound." The visual image of noise often helps to determine an appropriate means for noise control. There have been many attempts to fulfill this rather challenging objective. Theoretical or numerical means to visualize the sound field have been attempted and as a result, a great deal of progress has been accomplished, for example in the field of visualization of turbulent noise. However, most of the numerical methods are not quite ready to be applied practically to noise control issues. In the meantime, fast progress has made it possible instrumentally by using multiple microphones and fast signal processing systems, although these systems are not perfect but are useful. The state of the art system is recently available but still has many problematic issues; for example, how we can implement the visualized noise field. The constructed noise or sound picture always consists of bias and random errors, and consequently it is often difficult to determine the origin of the noise and the spatial shape of noise, as highlighted in the title. The first part of this paper introduces a brief history, which is associated with "sound visualization," from Leonardo da Vinci's famous drawing on vortex street (Fig. 1) to modern acoustic holography and what has been accomplished by a line or surface array. The second part introduces the difficulties and the recent studies. These include de-Dopplerization and de-reverberation methods. The former is essential for visualizing a moving noise source, such as cars or trains. The latter relates to what produces noise in a room or closed space. Another major issue associated this sound/noise visualization is whether or not we can distinguish mutual dependence of noise in space; for example, we are asked to answer the question, "Can we see two birds singing or one bird with two beaks?"

요 약

"소리의 비 가시성(非 可視性)"은 소음을 제어하고자 하는 공학자에게 주어진 근원적인 어려움 중의 하나이다. 따라서 이러한 비 가시성을 완화할 수 있는, 다시 말하면 소음을 볼 수 있는 방법에 대한

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탐구는 많은 관심과 시도가 있어왔다. 이들 방법 중 대표적인 것으로 이론적 또는 수치적인 방법을 이용하여 소음을 가시화 하려는 많은 시도를 들 수 있다. 수치적인 방법의 경우에는 난류 유동의 가시화 분야에서 괄목할 만한 성과를 이루어왔으나 난류 소음의 가시화에는 부족한 상태이다. 실험적인 방법의 경우는 마이크로폰 제작 기술의 발달로 인한 가격 인하로 많은 수의 마이크로폰을 손쉽게 확보할 수 있게 되었고 매우 빠른 신호처리 기술의 발달이 확보됨으로써 많은 진전이 이루어졌으나, 가시화된 음장 정보의 정확한 해석 등이 여전히 어려운 분야로 남아있다. 또한 음장 가시화 결과에는 항상 유한한 측정 자료로 인한 오차가 포함되어 있으며, 이로 인하여 논문의 제목에서 강조한 바와 같이 소음원의 탐지 및 소음원의 공간적인 분포를 결정하는 데 어려움이 있다. 이 논문은 음장 가시화와 관련된 간략한 역사를 레오나르도 다 빈치의 유명한 와류 유동 그림에서 출발하여 현대적 개념의 선형 혹은 평면형 마이크로폰 배열에 의해 수행되는 음향 홀로그래피 분야를 전반부에 설명하고, 음향 홀로그래피 구현에 있어서 발생하는 어려운 문제와 최근의 연구 동향을 후반부에 소개하는 방식으로 구성되어 있다. 최근의 문제 중에서는 자동차나 기차와 같이 이동하는 소음원을 가시화하기 위한 이동 후레임(moving frame)을 이용한 홀로그램 구성 방법과 닫힌 공간에서의 소음원 탐지를 위해 필요한 소리의 반사 효과 제거에 대하여도 기술하고 있다. 또한, 최근에 연구되는 또 다른 중요한 분야로서 "우리는 두 마리의 새가 지저귀는 것인지 아니면 한 마리의 새가 두 개의 목소리를 가지고 지저귀는 것인지 알 수 있을까?" 라는 질문으로 표현할 수 있는 공간상에 분포하는 소음원의 상호 의존관계를 구분하는 분야에 대한 문제 제기와 현실적인 접근 방법을 논하고 있다.

1. Brief History and Background

The title of this paper stems from the famous articles written by M. Kac(1): "Can one hear the shape of the drum?" This rather physically specific but mathematically general articles clearly addresses what the inverse problem, the relation between sound generation by membrane vibration and its reception in space, essentially means. In fact, the inverse problem can be regarded as "the attempts to obtain what is not available based on what is available." One can also find many different descriptions of the meaning of the "inverse problem" in the references.(2~8) Normally, in the inverse problem, the available data often are not sufficient to predict or describe what data are not measured. This circumstance is commonly referred as an "ill-posed problem" in the literature (for example, seethe references 1~19). Figure 2 well demonstrates what can happen in practice: the prediction totally depends on how well the basis function (the elephants or dogs in Fig. 2) mimics what happens in reality. When we try to see the shape of noise/sound sources, how well we see the shape of noise source completely depends on how well the basis function (the elephants or dogs in Fig. 2) mimics what happens in reality. When we try to see the shape of noise/sound sources, how well we see the shape of noise source completely depends on this basis function. This is simply because we predict what is not available by using the selected basis function.

Fig. 1 Leonardo da Vinci (1506-1510)'s sketch of turbulent flow. Image from http://www.eng.warwick.ac.uk/postgrad/msc-mods/msc-turbulent.htm

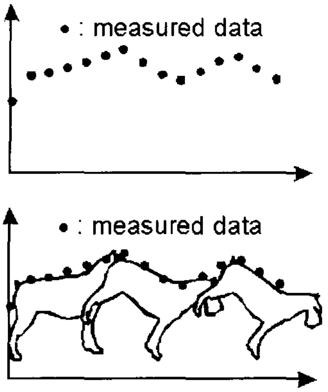


Fig. 2 The inverse problem and basis function. Are the measured data the parts of elephants or dogs?

Therefore, one of the common ways to classify the methods that are used in noise/sound source identification is to examine them with regard to the type of basis functions that are employed. One class can be regarded as the "non-parametric method" that uses the basis functions which do not model the signal. In other words, the method does not model the basis function to map the sound field that is not measured. All orthogonal functions fall into this category. One of the typical methods of this kind is concerned with the Fourier transform. Acoustic holography, in fact, uses this type of basis function. Therefore acoustic holography

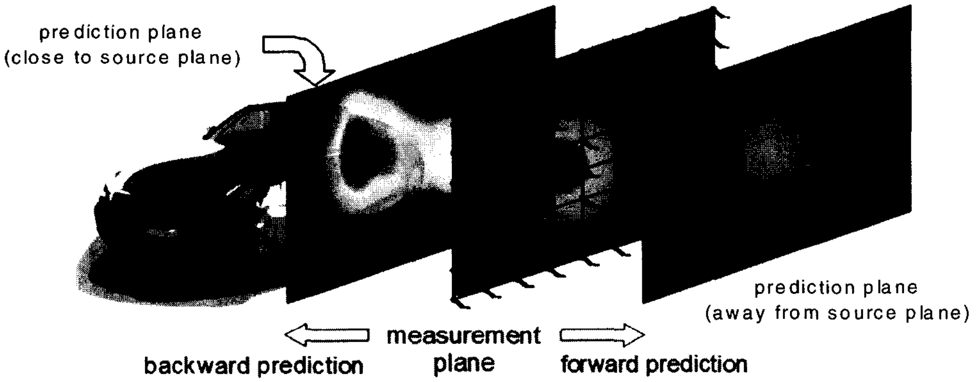


Fig. 3 Illustration of acoustic holography (The near field acoustic holography measures evanescent wave on the measurement plane.)

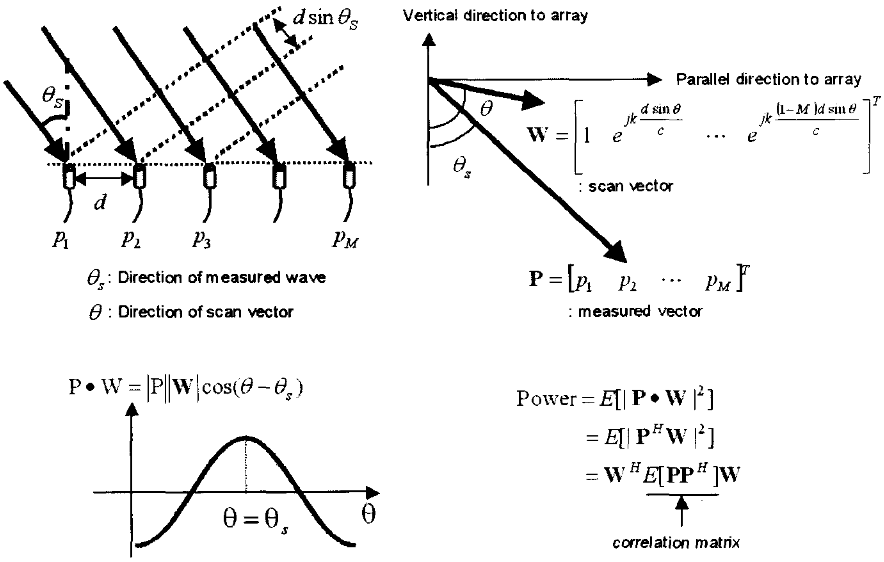


Fig. 4 The beam forming method

maps the sound field of interest with regard to every frequency that is measured: it sees the sound field in the frequency domain. In fact, the ideas of acoustic holography originated from Optics.(20~29) Acoustic holography simply extended or modified the basic idea of optical holography. Near-field acoustic holography(30, 31) has been recognized as a very useful means to predict the true appearance of the source (Fig. 3) (the near field effect on the resolution was firstly introduced in the field of microwave.(32)). The highlight of this method is to include, or measure the exponentially decaying waves as they propagate from the sound source, so that the method can completely reconstruct the sources.

Another typical method is often called the "parametric method." The name derives from the fact that these kinds of the methods model the signal using certain parameters. In other words, basis function is the "elephant" of Fig. 2. A typical method of these kinds is the "beam forming method." There can be different types of basis functions that can be used for the methods: it depends entirely on the sound field that the basis function tries to map.(33, 34) As illustrated in Fig. 2, we can select the elephant or others, depending on what we want to predict! This type of mapping gives us source location information. As illustrated in Fig. 2, the basis function maps the signal as changing its parameter: for the plane wave beam forming, this is an angle. The main issues that have been discussed for this kind of mapping methods are directly related to the correlation matrix structure that is simply the product of measured acoustic pressure vector and its complex conjugate (see Fig. 4 for the details). The method multiplies the scan vector, by changing its parameter: it is the angle of arrival for the plane wave of Fig. 4, to the correlation matrix as illustrated in Fig. 4. The scan vector is a basis function in this case. As one can see immediately, this problem is directly related to the structure of the correlation matrix and the basis function used. The signal to noise ratio of the measured correlation matrix determines the effectiveness of the estimation. There have been many attempts to improve the estimator's performance with regard to the signal to noise ratio.(34, 35) These methods have been mainly developed for application in radar and the under water community.(36) This technique has been also applied to a noise source location finding problem. High speed train noise source estimation(37~39) is one of the examples. Various shapes of arrays have been tried to improve its spatial resolution.(40~42) It is obvious that these methods have no correlation with seeing the shape of sound or noise source: they only provide us its location. Therefore, we will not discuss this type of method in this paper.

In the next section, the problems that we have discussed will be defined.

2. Problem Definitions

Acoustic holography consists of three components. One is measurement, which normally relates to measuring sound pressure on the hologram plane. The second is to predict the acoustic variables, including velocity distribution, on the plane of interest. The last part involves analyzing the holography. The last part has not been recognized as being as important as other parts in the past years. However, as indicated in the title of this paper, this part gives us what the sound picture really means: "Can we hear the shape?"

The issues associated with measurement are all related to the measurement configuration that constructs the hologram: we measure sound pressure on the discrete measurement positions and the measurement area is finite (finite aperture) as illustrated in Fig. 3. References(43~51) explain well the necessary steps to avoid spatial aliasing, wrap around error, and the effect of including evanescent waves on the resolution (Near-Field Acoustic

Holography). If we locate sensors incorrectly on the hologram surface, then this would induce errors on the predicted results. Similar errors can be produced when there are magnitude and phase mismatch between sensors. This is well summarized in the reference(52). There have been many attempts to reduce the aperture effect. One of these is to extrapolate the pressure data based on what is measured.(49, 51) Another measurement method actually allows the measuring of sound pressure in sequence and interpreting the measured sound pressures with respect to the reference signals, assuming that the measured sound pressure field is stationary during the measurement and the number of independent sources are smaller than the number of reference microphones.(53~60) Another measurement method actually allows scanning or moving the microphone array, therefore, extending the aperture size as much as one can.(61~64) This also allows measuring the sound pressure generated by the moving sound sources, such as regarding a vehicle's exterior noise.

The prediction problem is rather well defined and relatively straight forward. Basically, the solution of the acoustic wave equation usually results in the sound pressure distribution on the measurement plane. The prediction can beat tempted by using Green's function: for example see the Kirchhoff-Helmholtz integral equation. It is noteworthy, however, that the prediction depends on the shape of measurement and prediction surface, and also the presence of sound reflections.(53, 65~86)

The acoustic holography analysis problem has been introduced rather recently. As mentioned earlier in this paper, this is one of the essential issues connected to the general inverse problem. The basic question is to ask that what we see and imagine is related to what happens in reality. There are two different sound/noise sources: one is what is really radiating the sound and the other one is what is reflecting the sound. The former is often called "active sound/noise,"and the latter is "passive sound/noise." This is an important practical concept for establishing noise control strategy; we want to eliminate the passive noise source. The other issues basically are concerned with "Can we see two birds singing or one bird with two beaks?" The concept of an independent and dependent source has to be addressed properly to understand the issues.

3. Solution Methods

3.1. Prediction Process

Prediction process is related to how we can predict the unmeasured sound pressure or other acoustic variables based on the measured sound pressure information. The following equation relates the unmeasured and measured pressure.

$$P(\vec{x};f)=\frac{1}{4\pi}\int_{S_h}\left[\left.\frac{\partial p}{\partial n}\right|_{(\vec{x}=\vec{x}_h;f)} G(\vec{x}\,|\,\vec{x}_h;f) - p(\vec{x}_h;f)\frac{\partial G(\vec{x}\,|\,\vec{x}_h;f)}{\partial n}\right]dS_h . \qquad (1)$$

Equation (1) is the well-known Kirchhoff-Helmholtz integral equation, where $G(\vec{x}\,|\,\vec{x}_h;f)$ is Green's function. This equation essentially says that we can predict sound pressure anywhere if we know the sound pressures and velocities on the boundary (Fig. 5). However, it is noteworthy that measuring velocity on the boundary is more difficult than measuring sound pressure. This rather practical difficulty can be solved by introducing Green's function that satisfies the Dirichlet boundary condition: $G_D(\vec{x}\,|\,\vec{x}_h;f)$. Then, Eq. (1) becomes

$$P(\vec{x};f)=-\frac{1}{4\pi}\int_{S_h}P(\vec{x}_h;f)\frac{\partial G(\vec{x}\,|\,\vec{x}_h;f)}{\partial n}dS_h . \qquad (2)$$

This equation allows us to predict sound pressure on any plane of interest.

To see what essentially happens in the prediction process, let us consider Eq. (2) when the measurement and prediction plane are both planar: the planar acoustic holography assumes that the sound field is free from reflection (Fig. 6). Then we can write Eq. (2) as

$$P(x,y,z;f)=\int_{S_h}P(x_h,y_h,z_h;f)\times K_{PP}(x-x_h,y-y_h,z-z_h;f)\,dS_h, \quad (3)$$

$$\text{where}\quad K_{PP}(x,y,z;f)=\frac{1}{2\pi}\frac{z}{r^3}(1-jkr)\exp(jkr),$$

$$r=\sqrt{x^2+y^2+z^2},$$

$$k=\frac{2\pi f}{c}. \quad (4)$$

This is a convolution integral, and therefore, we can write this in wave number domain as

$$\hat{P}(k_x,k_y,z;f)=\hat{P}(k_x,k_y,z_h;f)\exp[jk_z(z-z_h)], \quad (5)$$

$$\text{where}\quad k_z=\sqrt{k^2-k_x^2-k_y^2}. \quad (6)$$

This equation essentially predicts sound pressure with respect to the wave number, (k_x,k_y,k_z). If $k^2\geq k_x^2+k_y^2$, the wave in z-direction (k_z) is propagating in space. Otherwise, the z-direction wave decays exponentially: it is an evanescent wave.

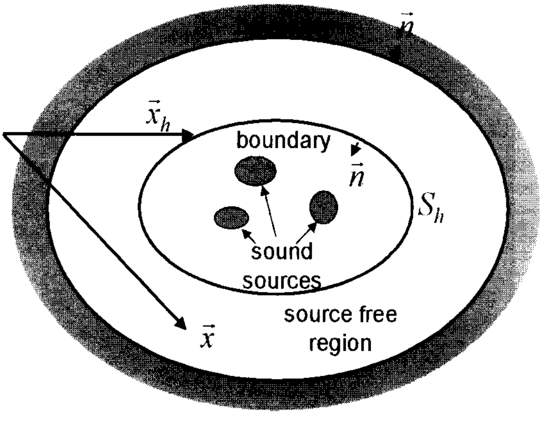


Fig. 5 Geometry and nomenclature for the Kirchhoff-Helmholtz integral equation

Equation (5) also allows us to predict the sound pressure on the source plane, when $z=z_s$. It is noteworthy that it is an inverse problem because it predicts pressure distribution on the source plane based on the hologram pressure (Fig. 6).

The issues related with the evanescent wave and its measurement are well addressed in the literature. For example, see reference.(87) The measurement of evanescent waves essentially allows us to have higher resolution than conventional acoustic holography.(88~93) However, it is noteworthy that the evanescent wave component is substantially smaller compared with other propagating components. Therefore, it is easy to produce errors that are associated with sensor or position mismatch(52); in other words, it is very sensitive to signal to noise ratio. The signal to noise ratio can be amplified when we try to reconstruct the source field: this is one of the typical ill-posed phenomena. Focusing on this problem, there have been many attempts to reduce this effect by using the spatial filter.(46, 91~98) It is often called "regularization" of acoustic holography: references(99~111) are those examples.

Depending on the separable coordinates that we

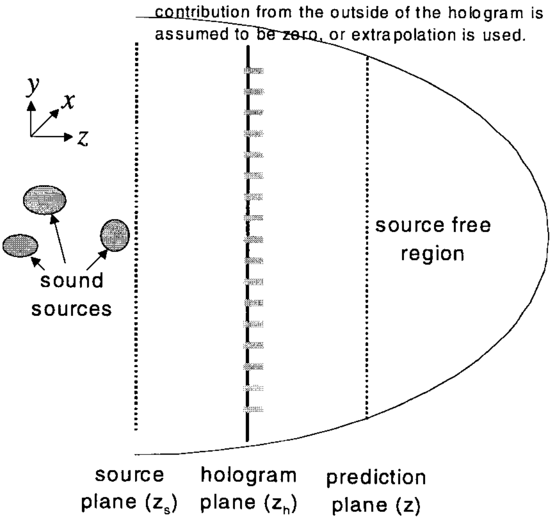


Fig. 6 Illustration of the planar acoustic holography

use for acoustic holography, we can construct cylindrical or spherical coordinates.(53, 66, 68) These methods predict the sound field in exactly the same manner as the planar holography does but with respect to the different coordinates. As we can expect, however, these methods have some advantages. For example, the wrap around error is negligible; in fact, there is no such error in the spherical acoustic holography, and no aperture related error.(53) Very recently, the advantage of using spherical function has also been introduced.(78, 80, 85, 86, 112)

3.2. Measurement

To construct the hologram, we commonly measure sound pressure at discrete positions as illustrated in Fig. 3. However, if the sound generated by the source, and therefore the sound field, can be assumed to be stationary, then we do *not have to measure them at the same time*. Figure 7(a) illustrates one way to accomplish this measurement.

This method measures the sound pressure field normally using line array in steps [Fig. 7(a)]. To understand the issues that are associated with this measurement system; for the sake of its simplicity, let us see how we process the signal when the signal is pure tone and there is a single source. The relation between sound source and sound pressure in the field, or measurement position can be written as

$$P(\vec{x}_h; f) = H(\vec{x}_h; f)Q(f), \qquad (7)$$

where $Q(f)$ is the source input signal and $H(\vec{x}_h; f)$ is the transfer function between the source input and the measured pressure. This means that if we know the transfer function and input, then we can find the magnitude and phase between the measured positions. Because it is usually not practical to measure the input, we normally use reference signals [Fig. 7(a)]. By using a reference signal, the pressure can be written as

$$P(\vec{x}_h; f) = H'(\vec{x}_h; f)R(f), \qquad (8)$$

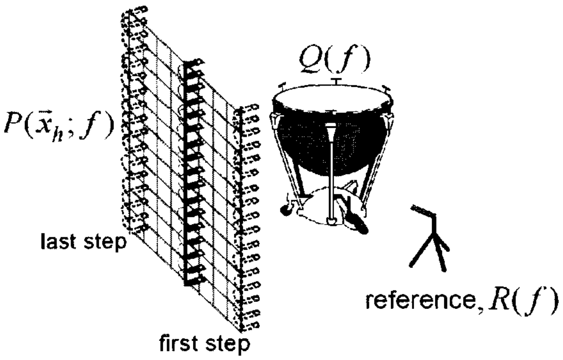
where $R(f)$ is the reference signal. We can obtain $H'(\vec{x}_h; f)$ by

$$H'(\vec{x}_h; f) = \frac{P(\vec{x}_h; f)}{R(f)}. \qquad (9)$$

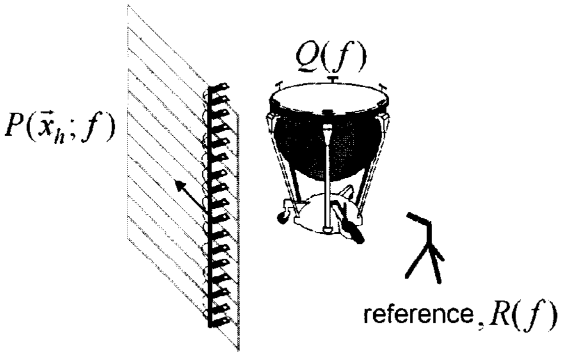
The input and reference has the relation of

$$R(f) = H_R(f)Q(f), \qquad (10)$$

where $H_R(f)$ is the transfer function between the input and reference. As a result, therefore, we can see that Eq. (8) is the same expression as Eq. (7).



(a) step-by-step scanning



(b) continuous scanning

Fig. 7 Two measurement methods of pressure on the hologram plane

It is noteworthy that Eq. (7) holds for the case where we have only one sound source and the sound field is stationary random. However, if the number of sound sources is two, then Eq. (7) has to be

$$P(\vec{x}_h;f)=H_1(\vec{x}_h;f)Q_1(f)+H_2(\vec{x}_h;f)Q_2(f), \quad (11)$$

where $Q_i(f)$ is the i-th input and $H_i(\vec{x}_h;f)$ is its transfer function. There are two independent sound fields. This requires, of course, two independent reference signals. It has been well accepted that the number of reference microphones has to be greater than the number of independent sources.(56) However, if this is strictly true, then this means that we have to somehow know the number of sources, and this, in some degree, contradicts what the acoustic holography provides us.

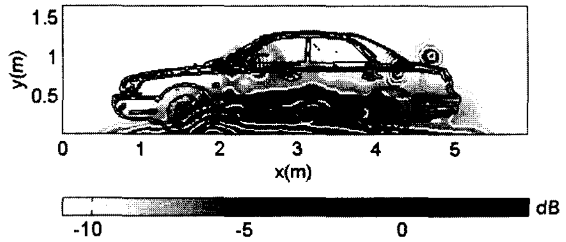


Fig. 8 Application result of the step-by-step scanning method to the wind noise of a car. This figure is the pressure distribution at 710~900 Hz on a source plane when the flow velocity is 110 km/h. In this experiment, 17 reference microphones are randomly located in the car

A recent study(60) demonstrates that measured information, where the sources are, and how many independent sources are, converge to true value as the number of reference microphones increases. This study also shows that the sources of high power are likely to be identified even if the number of reference microphones is less than the number of sources. Fig. 8 shows the example of this method when there are many independent sound fields.

On the other hand, a study shows that we can even continuously scan the sound field by using a line array of microphones.(61~64) [Fig. 7(b)] This method essentially allows us to extend the aperture size without any limit as long as the sound field is stationary: in fact, reference(64) also shows that this method can also be used for a slowly varying sound field: quasi-stationary. The method must involve the result of the Doppler shift.

For example, let us consider a plane wave in (k_{x0},k_{y0},k_{z0}) direction and a pure tone of frequency f_{h0} (Fig. 9). Then the pressure on the

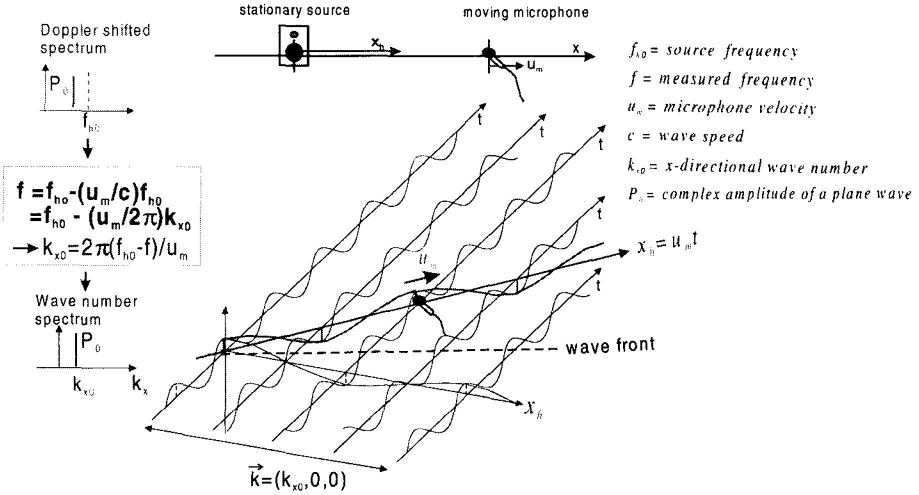


Fig. 9 The continuous scanning method for a plane wave and pure tone (one dimensional illustration)

hologram plane can be written as

$$p(x_h, y_h, z_h; t) = P_0 \exp[j(k_{x0}x_h + k_{y0}y_h + k_{z0}z_h)] \times \exp(-j2\pi f_{h0}t) \tag{12}$$

where P_0 denotes the complex magnitude of the plane wave. If a microphone is moving at the x-velocity of u_m, the measured signal $p_m(y_h, z_h; t)$ is

$$p_m(y_h, z_h; t) = p(u_m t, y_h, z_h; t). \tag{13}$$

By Eq. (12), the Fourier transform of Eq. (13) can be expressed as

$$F_T[p_m(y_h, z_h; t)] = P_0 \exp[j(k_{y0}y_h + k_{z0}z_h)] \times \delta\left(\frac{u_m}{2\pi}k_{x0} - f_{h0} + f\right). \tag{14}$$

Equation (14) means that the complex amplitude of the plane wave is located at the shifted frequency $f_{h0} - u_m k_{x0}/2\pi$, as shown in Fig. 9. In general, the relation between the shifted frequency f and x-directional wave number k_x is expressed as (Fig. 10)

$$k_x = \frac{2\pi(f_{h0} - f)}{u_m}. \tag{15}$$

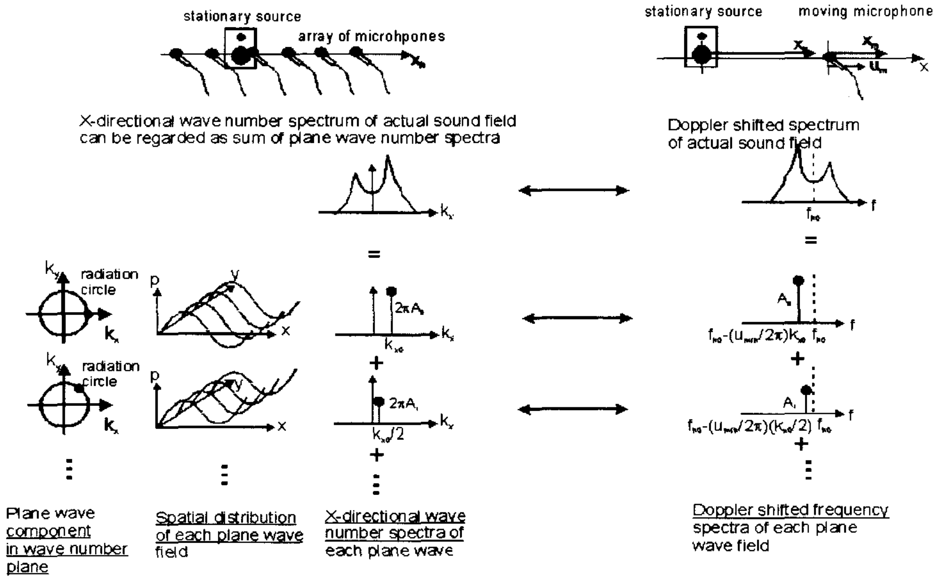


Fig. 10 The continuos scanning method for more general case (one dimensional illustration)

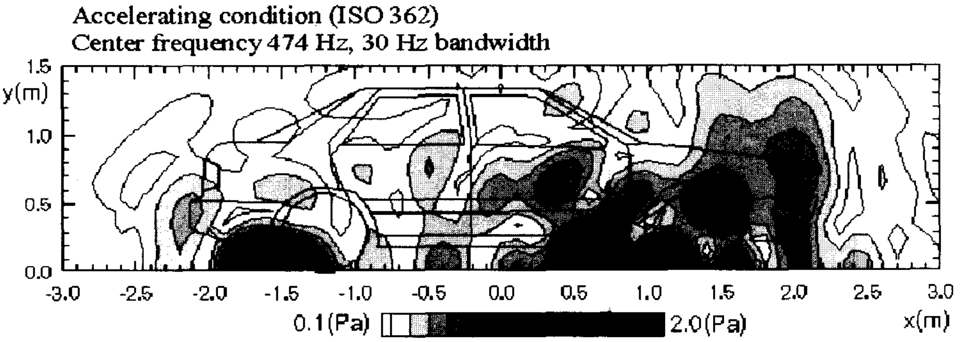
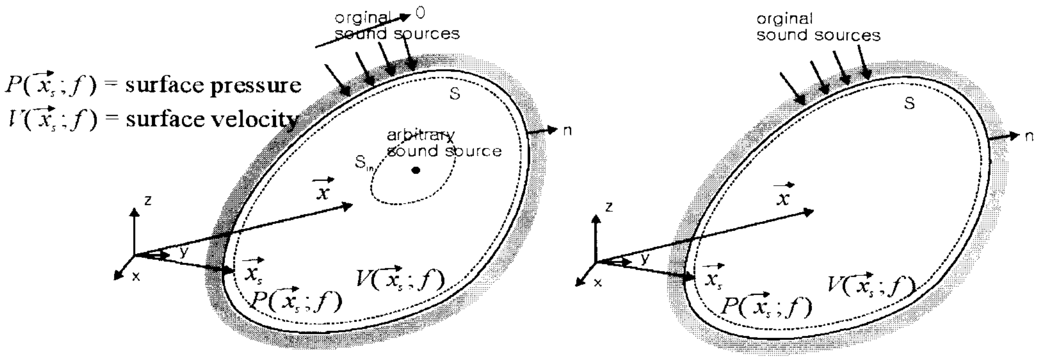


Fig. 11 Application result of the continuous scanning method to vehicle pass-by noise. The tire pattern noise distribution (pressure) on the source plane is shown when the vehicle is accelerated from 50 km/h

We can measure the original frequency f_{h0} by a fixed reference microphone. By the Doppler shift, therefore, we can obtain the wave number components from the frequency components of the moving microphone signal. This method essentially uses the relative coordinate between hologram and microphone. Therefore, it can be used for measuring a hologram of moving noise sources (Fig. 11). This is one of the major contributions of this method.(61~64)

3.3. Analysis of Acoustic Holography

Once we have a picture of sound, acoustic holography, then we immediately have a question about its meaning. What we have is usually a contour plot of sound pressure distribution or vector plot of sound intensity on a plane of our interest. We may have a suggestion about where the sound source is and how it radiates in space with respect to frequency of interest. However, in the strict sense, the only thing we can do from the two-dimensional expression of sound pressure or



(a) admittance measurement (b) source strength measurement

Fig. 12 Two steps to separate the active and passive source

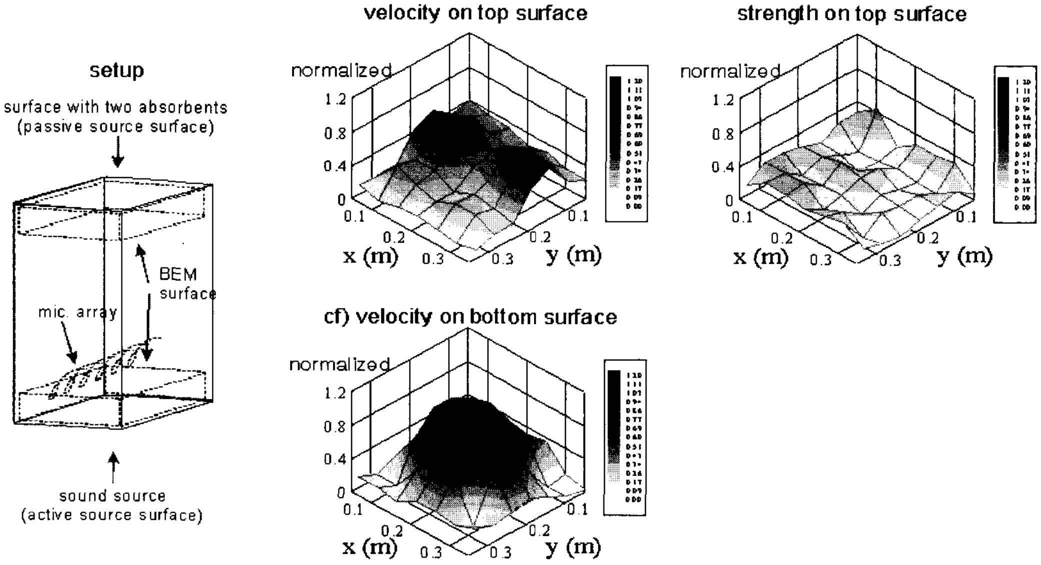


Fig. 13 Experimental result that separates the active and passive source. The top surface is made by sound absorption material. The speaker on the bottom surface radiates sound. The top surface source, which is reflecting sound, is eliminated by the separation

intensity distribution is to imagine what there really was. We do not know, precisely, where the sound sources are.

It is also noteworthy that there are two types of sound sources. One is what we may call an "active sound source," and the other is a "passive sound source" as we mentioned earlier. The former is the source that radiates sound by itself. The latter is radiating but just reflecting sound. These two different types of sound sources can be distinguished,(115) by eliminating reflected sound. This is directly related to the way to impose the boundary condition on our analysis problem.

The boundary condition of a locally reacting surface can be written as(115~117)

$$V(\vec{x}_s;f)=A(\vec{x}_s;f)P(\vec{x}_s;f)+S(\vec{x}_s;f). \qquad (16)$$

$V(\vec{x}_s;f)$ and $P(\vec{x}_s;f)$ is are the velocity and pressure on the wall. $A(\vec{x}_s;f)$ is the wall admittance and $S(\vec{x}_s;f)$ is the source strength on the wall. The active sound source is located at the position that the source strength is not zero. This equation says that we can estimate source strength if we measure the wall admittance. It is necessary to first turn off source or sources, and then measure the wall admittance by putting a known source in the position we desire [Fig. 12(a)]. The next step is to operate the sources and get the sound pressure and velocity distribution on the wall, using the admittance information [Fig. 12(b)]. This provides us what the location of the source is and how strong it is: the source power. For example, see Fig. 13.

Another very important issue is whether or not we can distinguish independent or dependent sources: "two birds singing" or "one bird with two beaks." This has a rather significant practical application. For example, to effectively control the noise sources, we only need to control independent noise sources. This can be done by using the statistical differences between the signals that are induced by the independent and dependent sound sources.

For example, let us consider a two-input/single-output system. If the two inputs are independent, the spectrum of the output is expressed as

$$S_{PP}(f)=|H_1(f)|^2\,S_{Q1Q1}(f)+|H_2(f)|^2\,S_{Q2Q2}(f), \qquad (17)$$

where $S_{QiQi}(f)$ is the spectrum of i-th input $Q_i(f)$ and $H_i(f)$ is its transfer function. The first and second terms represent the contributions of the first and second input to the output spectrum,

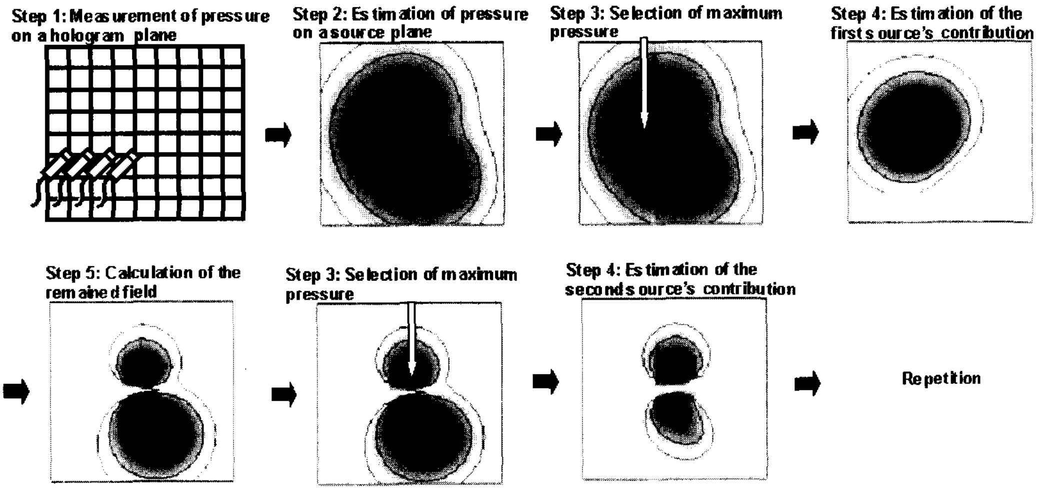


Fig. 14 Procedures to separate the independent and dependent sources

respectively. If we can obtain a signal as

$$W_1(f) = C(f)Q_1(f), \tag{18}$$

then we can estimate the contribution of the first source as[118]

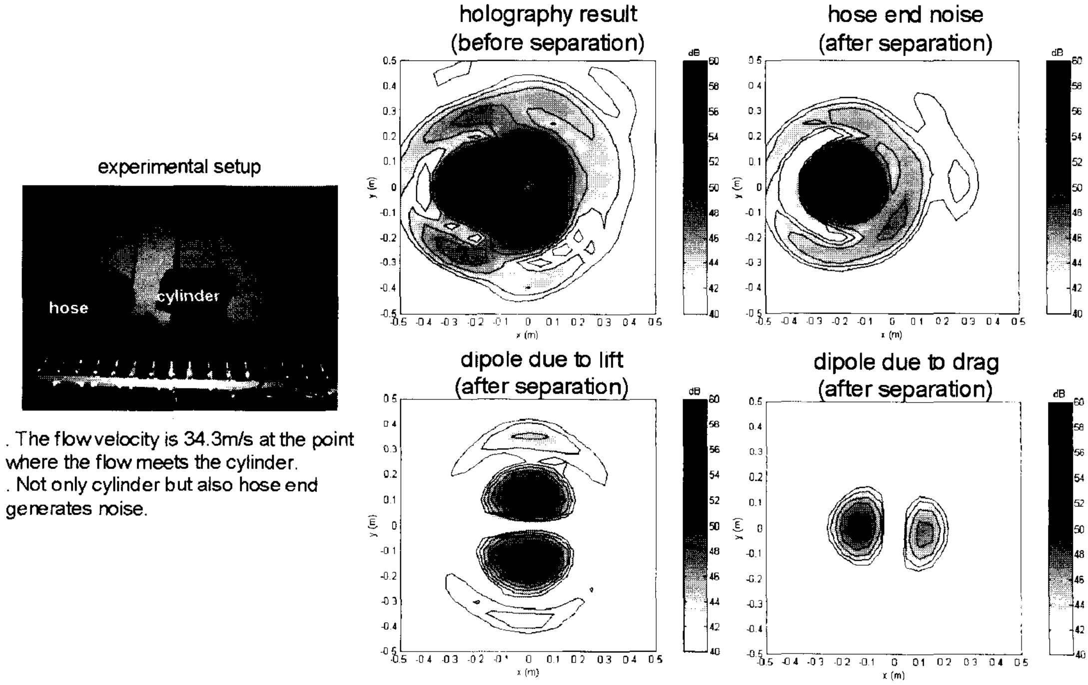
$$W_1(f) = C(f)Q_1(f), \tag{19}$$

where $\gamma^2_{W1P}(f)$ is the coherence function between $W_1(f)$ and $Q_1(f)$.

We can simply extend Eq. (19) to multiple output case. Acoustic holography is the case. The main tenet is how to obtain the signal that satisfies Eq. (18). We can loosely say that by putting sensors closer to the source or sources,(56, 57, 119~122) we may have a better signal that can be used to distinguish between independent or dependent sources. However, it is not well proved and not practical; it is not easy to put the sensors close to the sources. Very recently, a method that does not require this(123, 124) was developed. Figure 14 explains the method's procedures. The first and second steps are the procedures of acoustic holography: measurement and prediction. The third step is to search the maximum pressure on the source plane. The method assumes that the maximum pressure satisfies Eq. (18). The fourth step is to estimate the contribution of the first source by using the coherence functions between the maximum pressure and other points like Eq. (19). The fifth step is to calculate the remaining spectrum by subtracting the first contribution from the output spectrum. The steps are repeated until the contributions of other sources are estimated. For example, see Fig. 15.

4. Concluding Remarks

As we all expected, we cannot simply say "Yes," or "No" on the question that was raised by the title of this paper. However, we now understand that the "analysis" of what we obtained; acoustic holography, has to be properly addressed.



. The flow velocity is 34.3m/s at the point where the flow meets the cylinder.
. Not only cylinder but also hose end generates noise.

Fig. 15 The separation method is applied to a vortex shedding experiment (1 kHz)

In fact, we did not give much attention to this problem. We now know a bit better how to obtain information from the sound picture. Making a picture is the job of acoustic holography for our case, but the impression on the picture belongs to whomever sees the picture. However, this paper certainly provides some useful guidelines to receive the correct impression, or the right information from the picture. Further studies will provide better ways to see the sound picture in the near future.

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