[N502] Measuring Method of Sound Reflection and Absorption Characteristics Based on the Particle Velocity and its Applications to Measurements on Such as Drainage Pavement of Road Surface

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ABSTRACT

Both of sound pressure and particle velocity are took account equally in the acoustic theory. But, almost sound measurements depend on only sound pressure, and particle velocity is hardly measured. It seems that measurement of particle velocity is difficult at present time. If the measurements of particle velocity become easy and popular, application targets will be opened in very wide ways. So, we propose theoretically and concretely new measuring method of particle velocity and introduce some applications based on the measurement of particle velocity. As the suitable examples, we tried the field measurements of the sound absorption coefficient of drainage pavement of road surface, which is expected as effective measures against heavy road traffic noise in urban area. High sound absorption characteristics are shown around frequency of 1 kHz. This result confirms to the noise reduction as well known as effects of the porous drainage pavement. As other applications, the typical absorptive material of glass wool and the resonator with clear peak of the sound absorption are introduced. Conclusion is that the new way is effective to evaluate the sound absorption characteristics of acoustic materials.

KEYWORDS: Particle velocity, Acoustic Admittance, Impedance, Sound absorption, Drainage pavement

INTRODUCTION [1]

Sound pressure and particle velocity are equally treated in the acoustics as sound intensity defined by multiplication between both. However, only sound pressure is measured at the actual many occasions...
of acoustical researches and analyses, and particle velocity is hardly measured. In the history of acoustics, there were sensing aids for sound particle velocity such as Rayleigh disc and velocity microphone, but they had not developed. Even there is an imitative measurement method by the differential output from a pair of microphones, it seems that measurement of the particle velocity is very difficult. Author thought of that application range of acoustic measurement spreads if the measurement of the sound particle velocity would become possible, and actually tried the measurement of the sound particle velocity. In this paper, we introduce some tried methods and results.

**PRINCIPLE OF MEASUREMENT ON SOUND PARTICLE VELOCITY**

When the pair of microphones with equal sensitivity and the small interval of $\Delta r$ are arranged close to a test target as show in Fig.1 (A). Plane wave sound field is supposed here. Both incident and reflected waves can be separated from the two microphone’s outputs with the phase delay operation corresponding to the small interval. Then, the sound reflection coefficient can be obtained from the amplitude ratio between incident wave and reflected wave. Acoustic impedance and sound absorption coefficient can be continuously obtained.[2,3]

In more general, a particle velocity $u$ is defined by the following Eq.(1).

$$u = -\frac{1}{\rho} \int \frac{\partial p}{\partial r} dt = -\frac{1}{\rho} \int \frac{\Delta p}{\Delta r} dt = -\frac{1}{i\rho\omega} \frac{p_a - p_o}{\Delta r} \quad \text{(1)}$$

$$p = \frac{(p_a + p_o)}{2} \quad \text{(2)}$$

Then, approximate measurement of the sound particle velocity becomes possible from the differential output $\Delta p$ and the angular frequency $\omega$ of the test sound wave. Sound intensity can be obtained from the multiplication between both approximate values $u$ and sound pressure $p$. Acoustic admittance or acoustic impedance can be obtained from the relation as Eq.(3) or Eq.(4). As shown in Fig.1 (B), both of a sensor that can measure particle velocity directly and a microphone are arranged close to each. Acoustic admittance $b$ and acoustic impedance $z$ can be directly measured just by definitions as below. Sound reflection ratio $r$ and sound absorption coefficient $\alpha$ are also obtained by each definition.

$$\dot{b} = \frac{u}{p} \quad \text{(3)}$$

$$z = \frac{1}{\dot{b}} \quad \text{(4)}$$

$$r = \frac{(z - 1)}{(z + 1)} \quad \text{(5)}$$

$$\alpha = \frac{1}{|r|^2} \quad \text{(6)}$$

**TRIAL OF THE PARTICLE VELOCITY MEASUREMENT**

By basis of surface vibration of thin film

Pair microphones method seems the advantageous technique at these days, but long interval between...
pair microphones is required to keep enough sensitivity at the low frequency. Authors conclude from such a requirement that very close arrangement of microphones to the observation object is impossible, and we considered the realization of other measuring methods.

First proposition is the observation method of the membrane vibration on a thin film which will be excited by particle velocity or pressure-gradient in an object sound field. Principle of this method can be based on the simple vibration dynamics model related between force and acceleration as below. When the film with density of \( \rho_m \), thickness of \( \Delta t \) and mass per unit area of \( m \) is arranged and the force per unit area \( f \) loads between both front and rear surfaces as sound pressure difference \( \Delta p \), acceleration \( \alpha_m \) occurs. Sound particle velocity can be related to the surface velocity on the film as follows.

\[
\begin{align*}
    f &= m\alpha_m \quad \text{(7)} \\
    \Delta p &= \frac{\partial p}{\partial r} \Delta t = -m\frac{du_m}{dt} \quad \text{(8)} \\
    \left( -j\rho_0\omega_m \right) \Delta t &= \rho_m \Delta t \cdot \left( -j\omega_u \right) \quad \text{(9)} \\
    u &= \frac{\rho}{\rho_m} u_m \quad \text{(10)}
\end{align*}
\]

According to this measurement model, the sound particle velocity \( u \) can be obtained from the observed surface vibration velocity \( u_m \) on the film. In this model, sensitivity is decided by the ratio between the density of the air \( \rho \) and density of the film material \( \rho_m \). Therefore, the lightness of film is very important. As for the actual composition, the sensitivity declines because tension is added to the film and effective mobility declines. Multiple modal vibrations occur on the surface, and their influences on the observation can’t be ignored any more. Membrane vibration should be measured in the no-load condition.

**Trial of membrane vibration method**

We actually tried measurements based on the above considerations. The first experiment object was a Helmholtz’s resonator. A small circular thin film was made by the plastic film used for food preservation, and it was arranged in and near the bottleneck. Measurement block diagram and observed examples are shown in Fig. 2. Vibration velocity on the film was measured by a laser vibrometer. As mentioned in the textbook of the acoustics, strong aerial vibration in the bottleneck can be con-

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Fig. 2 Application example of sound particle velocity measurement to investigations of acoustic properties of the Helmholtz’s resonator
firmly at near the theoretical resonance frequency.

As the next step, measurements on the sound absorption coefficient were tried in a room with area about 50 m². Some kinds of glass wool with density 32 kg/m³ and with area of about 900x1000 mm² were selected for the fundamental experiment objects. Each of them was laid on the floor, and both of the thinner mirror film formed to the circle with diameter 12.5 mm and the small microphone with the diameter of 10 mm were arranged on the test object. Tension was slightly added to the film to keep the flat surface for the laser light reflection. White noise was radiated from the height of about 1 m, and the transfer functions of the vibration velocity to the sound pressure were analyzed. Obtained values were meant relative admittance. To make the calibration value for this method, white noise was radiated from indoor side to outdoor side through an opened window of the test room, and the analyzed relative admittance would be supposed as under the condition of acoustic impedance ratio to be 1.

Acoustic impedance, complex reflection coefficient and sound absorption coefficient were obtained from these analysis results and by relations as from Eq.(3) to Eq.(6).

Measured examples of the relative acoustic admittance, impedance ratio and the sound absorption coefficient are shown in Fig.4, Fig.5 and Fig.6. Frequency dependences of the typical porous material can be recognized. But, there are strong disorders partly such as that sound absorption coefficient falls into 0 at the frequency higher than 1 kHz. Cause of the strong disorder is modal resonant vibrations on...
the thin film with added certain tension. In this experiment, the analyzed coherency value was insufficient in the frequency range lower than about 400 Hz. It would be caused by the lack of the apparent total sensitivity including both of the weak excited vibration on the film and the sensitivity of the laser vibrometer. How to make a film surface and its frame will be future subject for the developing this method. The obtained sound absorption coefficient by this method is higher than typically obtained values by the sound tube method, and smaller than typically obtained values by the reverberation room method. It isn’t clear whether such a tendency is caused by the measurement environment or by this technique itself.

**Use of the hot wire type particle velocity sensor**

Authors had opportunity to use the hot wire type Microflown’s particle velocity sensor made by the semiconductor manufacturing technology. Frequency characteristics of its sensitivity are flat in the lower frequency range up to about 500 Hz as shown by bottom curve in Fig.7. As for the high frequency range, the sensitivity is reducing with increasing of frequency, and such a tendency becomes stronger in higher frequency range. Directional characteristic pattern as letter of 8 was confirmed. Relations between the incidence direction of the sound wave and the phase polarity of the sensor output were confirmed. To correct the frequency dependence of sensitivity to make apparent flatness, filter circuit with strengthen gain in high-frequency range more than 1 kHz was prepared.

Both of a particle velocity sensor and a sound pressure microphone were set on a test object, and then transfer function of the sensor output against the microphone output was analyzed. The same calibration way as the case of using the thin film was performed, and the analyzed result was used for the calibration to obtained acoustic admittance.

The analyzed relative admittance as the particle velocity to the sound pressure and corrected by the emphasis filter for the calibration are shown by upper curve in Fig.7.

**Experiment results on drainage pavement [4]**

Preliminary experiments were tried in the same room as when using thin film method. The outline of measurement is shown in Fig.8. Two kinds of test object of drainage pavement with thickness of 40 mm
were selected for the experiment. The set of the microphone and the particle velocity sensor was located just on each object surface. White noise was radiated from the point of height about 1 m above each object, and each surface admittance was obtained from the transfer function analysis. The analyzed relative sound admittances obtained in the experiment are shown in Fig.9 with two reference values. One of two reference values is the value for calibration and another is measured value just on the floor surface which is supposed to be perfect reflector. In general, material has value between both reference values, and the sound absorption coefficient of the material increase when measured admittance value closes to the calibration value, and decrease when to that on the floor surface. The admittance values of this experience approached the calibration value at the near frequency of 800 Hz, and sound absorption coefficients corresponding to such admittance were calculated. The sound absorption coefficients moving averaged by 1/12 octave band width are shown in Fig.10. These results have high sound absorption around the frequency of 800 Hz, and show the characteristics on the typical drainage pavement. [4,5] By these experiments, it was found that the measuring method using a hot wire type particle velocity sensor would be effective for practical use.

APPLICATION TO THE FIELD MEASUREMENT

Sound absorption characteristics of drainage pavement
We tried field measurement on the sound absorption of the actual drainage pavement on the test road track of the NILIM (National Institute for Land and Infrastructure Management). Measuring objects are five kinds of pavement as single drainage layer type, two kinds of double drainage layer type, porous elasticity layer type and ordinary dense asphalt type for the reference. In accordance with this experiment, the running noises of the passenger car were measured to investigate the actual influence of each pavement condition to the road traffic noise. Measurement examples by the particle velocity method are shown in Fig.11. Concerning the drainage pavements, it is clear that each sound absorption coefficient is high at around the frequency of 850 Hz. While concerning the porous elasticity pavement, it is clear that sound absorption coefficient is high
around the frequency of 1.9 kHz as two times higher than the case of ordinary drainage pavement.

For the comparison, the sound absorption coefficients were measured by the separating a reflected wave from the incident wave by using a pair of microphones. Obtained results are shown in Fig.12. It is found that high sound absorption characteristics can be recognized for each drainage pavement condition. As for the frequency ranges where sound absorption coefficient is low, there are strong dispersions in each measured result. According to the comparisons of the results, it can be judged that particle velocity method is superior to the pair microphones method to recognize low sound absorptive condition.

We often hear that the noise reduction effect of the drainage pavement in the city street lose by clogging in the short time passage after construction. So, field measurement about the sound absorption characteristics of the drainage pavement was performed on a city road where reduction effect on the running vehicle’s noise had been lost in the short one year after pavement reconstruction. Particle velocity sensor method was used for this case. Measured sound absorption coefficients are shown in Fig.13.[6]

No difference with low sound absorptions between the drainage pavement and dense asphalt is shown. Measurement by the particle velocity method makes sure concerning with low sound absorption condition, and it will be very effective for the monitoring technique to keep the effect of the drainage pavement.
Other suitable examples
If contents of observation are limited to qualitative analyses of the sound reflection or sound absorption, we can take count only on the relative admittance without calibrating operation. Even such a case, irregularity of the spectrum of sound source can be automatically corrected because this method is based on relative analyzing referred to the actually received microphone output. Examples of observed relative admittance are shown in Fig.14 on the surface of imitated wall of the slit type structure. Sound resonance characteristics are recognized from the sharp peak near frequency of about 1 kHz. The particle velocity at the peak frequency relatively weakened by the insertion of glass wool into the back air space and absorptive range of frequency is spreading especially to the lower frequency side.

CONCLUSIONS

We proposed theoretically and concretely the measurement methods of sound particle velocity and introduced some kinds of application, and conclusions of this study are as follow.

1. Measurement methods of the particle velocity were available even incomplete at this time.
2. Synchronous measurement of particle velocity and sound pressure directly makes acoustic admittance or acoustic impedance just as by each definition.
3. We applied to measurement of absorption of fundamental porous material glass wool and to practical one of drainage pavement. We could confirm the typical absorptive characteristics.
4. The new methods will be effective to evaluate the sound reflection or absorption characteristics for many kinds of acoustic materials and structures.

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