TWO KINDS OF STATIC AND DYNAMIC STATE ESTIMATION METHODS BY USING WIND SPEED INFORMATION IN ENVIRONMENTAL LOW-FREQUENCY NOISE MEASUREMENT

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ABSTRACT Two kinds of static and dynamic state estimation methods are newly discussed for the problem of the measurement disturbance of environmental low-frequency noise in the presence of wind-induced noise. First, the probability characteristics of wind-induced noise are discussed in the form of probability distribution conditioned by wind speed, based on the simultaneous observation of the wind-induced noise and wind speed near a microphone. Next, especially from the viewpoint of simplicity for practical use, two kinds of static and dynamic state estimation methods are discussed. The static estimation method using the information on wind speed is fundamentally supported by the conservation principle of energy sum. The dynamic one is the method by using a recursive digital filter with the parameters successively renewed by the information on wind speed. This can be also simplified by using well-known Kalman filter under the assumption of the Gaussian distribution. The effectiveness of proposed two estimation methods are shown through experiments under a breezy condition in the open field.

1. INTRODUCTION

Wind-induced noise or wind noise is an inevitable disturbance that appear in the outdoor measurement of low-frequency acoustic noises under windy conditions. It is difficult to remove the low-frequency components of the wind noise by using usual windscreens of sound level meters. However, the outdoor measurement of the low-frequency noise was still recommended to be carried out in windless conditions in a recent proposal1). Nonetheless, the necessity of measuring the outdoor low-frequency noise (objective sound) from some noise sources arises frequently even under windy conditions. In such cases, some other countermeasures against the wind noise are required to undertake an accurate measurement.

The measurement method of putting a microphone near the ground surface is sometimes effective, but it is not always an essential countermeasure. The synchronized integration method is useful where the objective signal is able to be artificially intermitted in a constant wind noise. The method using a coherent detector2) is also effective but the objective signal is required to be sinusoidal. Furthermore, the dynamical estimation methods based on the Bayesian type digital filter2),3) are effective for the evaluation of arbitrary probability distribution types of the objective signal, but their algorithms are fairly complicated for practical use. Thus, there is much left to study on how to simply extract the wind noise from the observed sound, especially from the stand point of practical use.

We have already reported two simple estimation methods of static and dynamic types in the time domain and another simple estimation method in the frequency domain[4)~6)]. In this study, in order to find out more precise estimation methods, we discuss further characteristics of the wind noise in the first. In the next, two kinds of static and dynamic estimation methods for the objective noise contaminated by the wind noise are proposed. Finally, some of the experimental results on trial are shown.

2. WIND NOISE

The wind noise is composed of two components. The first component is the "pressure turbulence" generated by the microphone or the added windscreen located in an airstream of the wind. The spectrum of this component usually occupy a higher part of the spectral contents of wind noise and it is dependent on the wind speed. The second component is windborne turbulence in atmospheric pressure in the vicinity of the microphone. The spectrum of this component is considered to be low frequency dominant from the indication of an experimental result on a wind turbulence measurement. Part of this component under windy conditions is also considered as dependent on the wind speed, because much of the turbulence is originally generated by large structures or natural objects in the wind stream and is carried with the wind, although relaxing with time. Thus, the wind noise, consisting of these two components above, is expected to be in considerable correlation to the wind speed.

Examples of the wind noise and the wind speed observed for 10 minutes (600 seconds) are shown in Fig. 1. The wind noise is measured by a microphone with a wind screen and the wind is measured by a wind sensor in the vicinity of the microphone. The sound pressure levels of the wind noises in every one octave frequency ranges are shown. This figure shows that the wind noise over a wide frequency range varies with time and it is considerably dependent on the wind speed. The cross-correlation between the band components of the wind noise and the wind speed are shown in Fig. 2.

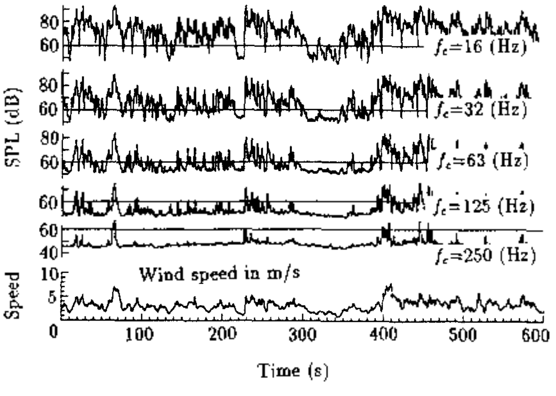

Fig. 1 Example of observed octave band wind noises and the wind speed: the center frequencies of each octave bands are f_c=16, 32, 63, 125, 250 (Hz).

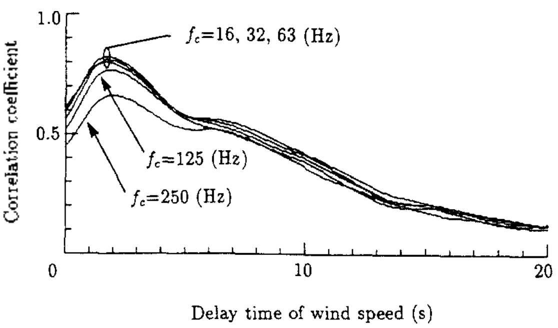

Fig. 2 Cross-correlation coefficient of the octave band wind noises correlated with the wind speed observed near the microphone.

Now, based on the above experimental fact, let us evaluate the wind noise by employing the positive use of the information on the wind speed. Let ν be the wind noise (sound pressure or mean square sound pressure) and w be the wind speed in the vicinity of the microphone, then the conditional probability distribution function (abbr. c.p.d.f.) of the noise can be expressed as $P(\nu|w=\alpha)$ conditioned by the wind speed $w=\alpha$. For example, the mean value $\mu(\alpha)$ and the variance $N(\alpha)$ are given as follows (the mean value is zero when the noise is observed in the sound pressure):

$$\mu(\alpha)(\triangleq < \nu|\alpha >) = \int_{-\infty}^{\infty} \nu \, dP(\nu|w=\alpha) \ , \tag{1}$$

$$N(\alpha)(\triangleq < (\nu-\mu(\alpha))^2|\alpha >) = \int_{-\infty}^{\infty} (\nu-\mu(\alpha))^2 \, dP(\nu|w=\alpha) \ . \tag{2}$$

Let $S_V(f)$ be a short time power spectrum component of the wind noise of frequency f for averaging time ΔT which is related to a response time of the sound level meter. The spectrum of wind noise $S_V(f)$ usually varies with time having a strong correlation with the wind speed w and it also fluctuates naturally even when the wind speed is constant. Hence, we introduce again the c.p.d.f. $P(S_V(f)|w=\alpha)$ of wind noise spectrum to express its whole fluctuation statistically assuming a wind speed $w=\alpha$. In particular, the mean power spectrum $\mathcal{S}_V(f,\alpha)$ is calculated as:

$$\mathcal{S}_V(f,\alpha)\,(\triangleq < S_V(f)|\alpha >) \int_{-\infty}^{\infty} S_V(f) \, dP(S_V(f)|w=\alpha) \ . \tag{3}$$

Thus, if the c.p.d.f of these values of the wind noise are previously known through the experiments on only the wind noise and the wind speed measurement, the probability distribution of these respective values of a latent objective signal at an actual measurement under windy conditions can be statistically estimated by using the wind speed information.

On the other hand, Fig. 3 shows the correlation relationship among three octave bands of the wind noises. It can be seen that fairly strong correlations exist between these band wind noises. Hence, in the case when the frequency range of the objective signal and background noise are limited and some frequency components of the wind noise are clearly separated from the other sound, such relationship is positively used to estimate the remaining components of the wind noise from one to the other. Concretely, let the mean square sound pressure of a octave band wind noise of which center frequency is f_a be $\overline{V}_a$; let the other octave band wind noise of the center frequency f_b be $\overline{V}_b$. Then, we can express the c.p.d.f. $P(\overline{V}_b|\overline{V}_a)$ of the other octave band wind noise on knowing the octave band wind noise $\overline{V}_a$. Here, if some octave band wind noises are practically measured, the objective sound of other frequency band which are contaminated by the wind noise at the same time can be estimated by using the above c.p.d.f.

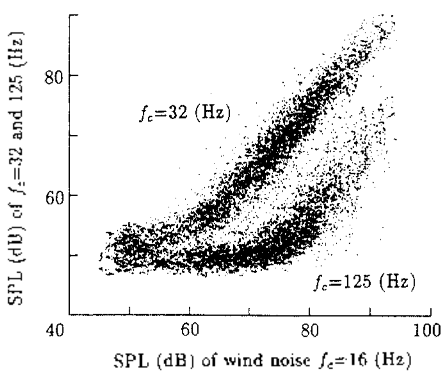

Fig. 3 Correlation diagram among the octave band wind noises of which center frequencies are f_c=16, 32, 125 (Hz).

3. ESTIMATION METHODS

3.1 Static Method

Several static methods estimating the objective sound from the mixed observation of the objective sound and the wind noise can be considered. Now, let us show only one simple static method based on the power spectrum analysis in the following.

Let $S_X(f)$ be the power spectrum component of the objective sound and let $S_Y(f)$ be that of observed sound. Since the objective signal is considered to be independent of the wind noise, the power spectrum component of observed sound can be simply given as the following equation:

$$S_Y(f) = S_X(f) + S_V(f) \ . \tag{4}$$

The conditional mean $\mathcal{S}_Y(f, w = \alpha)$ of the observed sound $S_Y(f)$ is calculated similar to that of the wind noise as:

$$\mathcal{S}_Y(f, w = \alpha) \triangleq \int_{-\infty}^{\infty} S_Y(f)\, dP(S_Y(f)|w = \alpha) \ , \tag{5}$$

introducing c.p.d.f. $P(S_Y(f)|w = \alpha)$ assuming the same wind speed $w = \alpha$. Hereupon, the conditional mean spectrum component $\mathcal{S}_X^*(f, w = \alpha)$ of the objective signal is estimated based on Eq. (5) as:

$$\mathcal{S}_X^*(f, w = \alpha) = \mathcal{S}_Y(f, w = \alpha) - \mathcal{S}_V(f, w = \alpha) \ . \tag{6}$$

where $\mathcal{S}_V(f, w = \alpha)$ is calculated using the wind information from Eq. (4). The corresponding mean square sound pressure value $\overline{X}^*(w = \alpha)$ and its SPL value $L_{X^*}(w = \alpha)$ at the wind speed $w = \alpha$ are calculated respectively from the estimates as:

$$\overline{X}^*(w = \alpha) = K \int_0^{\infty} \mathcal{S}_X^*(f, w = \alpha)\, df \ , \quad L_X^*(w = \alpha) = 10 \log_{10} \frac{\overline{X}^*(w = \alpha)}{{p_0}^2} \ . \tag{7}$$

The average SPL of the objective sound L_X^* can be easily calculated by averaging the $L_{X^*}(w = \alpha)$ over the wind speed w.

3.2 Dynamic Method

Next, let us consider an estimation method for the octave band objective sounds which are observed through octave band filters and let us consider the actual case that the objective sounds are not constant. Here, we cannot employ the addition rule of the ensemble averages as the basic principle of estimation based on the constant property of objective noise.

Now, let the variables be the sound pressure of one octave frequency band of b; let us express x_t^b, v_t^b and y_t^b be the objective sound, the wind noise and the observed sound at time t respectively; let w_t be the wind speed near the microphone. Originally, if we intend to express the probability distribution function of these variables, we must notice the whole of information on non-Gaussian distribution. However, let us approximate the random variables as that of Gaussian distribution in this study:

$$\bar{y}_t^b \triangleq E[y_t^b] = 0, \ \bar{x}_t^b \triangleq E[x_t^b] = 0, \ \bar{v}_t^b \triangleq E[v_t^b] = 0,$$
$$Y_t^b \triangleq E[(y_t^b)^2], \ X_t^b \triangleq E[(x_t^b)^2], \ V_t^b \triangleq E[(v_t^b)^2]. \tag{8}$$

Hence, we can employ well-known Kalman filter as one of dynamic state estimation methods. First, let us consider to estimate the state of wind noise instead of that of objective sound. Following to the original addition property of sound pressure, the observation equation can be directly expressed as:

$$y_t^b = x_t^b + v_t^b. \tag{9}$$

Next, the system equation of wind noise is approximatively derived as an AR model of first order:

$$v_{t+1}^b = F_t^b v_t^b + G_t^b u_t, \tag{10}$$

where u_t is the system input of Gaussian distribution ($\bar{u}_t \triangleq E[u_t] = 0$, $U_t \triangleq E[{u_t}^2] = 1$). Also, F_t^b and G_t^b are two system parameters that are determined in advance by the experimental results on the wind noise and the wind speed. That is:

$$F_t^b = \rho_{v^b}(n+1)/\rho_{v^b}(n) \quad (n = 0, 1, 2, \cdots) \ , \quad \rho_{v^b}(n) \, (\triangleq E[v_j^b v_{j+n}^b]/E[(v_j^b)^2]) \ ,$$
$$G_t^b = (1 - F^b)\sqrt{V_t^b} \ , \quad V_t^b = V^b(w_t) = \int_{-\infty}^{\infty} (v^b)^2 \, dP(v^b | w = w_t) \ . \tag{11}$$

The variance of the wind noise can be considered to be locally stationary, since the wind speed varies slowly within the sampling interval. Then, we approximatively obtain the variance of objective noise X_t^b by using the observed noise within the adequate time duration $[t - k + 1, t]$ that is assumed to be locally stationary:

$$X_t^b \simeq Y_t^b - V_t^b \ , \qquad Y_t^b \simeq ((y_{t-k+1}^b)^2 + (y_{t-k+2}^b)^2 + \cdots + (y_t^b)^2)/k \ . \tag{12}$$

From these parameters obtained above, the estimate of wind noise $\hat{v}_t^b$ can be obtained by employing Kalman filter as follows:

$$\hat{v}_t^b = \tilde{v}_t^b + P_t^b (X_t^b)^{-1} \{y_t^b - (\tilde{v}_t^b + \bar{x}_t^b)\} \ , \quad \tilde{v}_t^b = F_{t-1}^b \hat{v}_{t-1}^b + G_{t-1}^b \bar{u}_{t-1} \ ,$$
$$P_t^b = ((M_t^b)^{-1} + (X_t^b)^{-1})^{-1} \ , \quad M_t^b = (F_{t-1}^b)^2 P_{t-1}^b + (G_{t-1}^b)^2 U_{t-1} \ . \tag{13}$$

where $\tilde{v}_t^b$ is the predicted value of wind noise at a time $t - 1$, P_t^b is the variance of estimation error and M_t^b is the variance of prediction error. Finally, the estimate of objective noise $\hat{x}_t^b$ is obtained by the observation equation:

$$\hat{x}_t^b = y_t^b - \hat{v}_t^b \ . \tag{14}$$

4. EXPERIMENTAL RESULTS

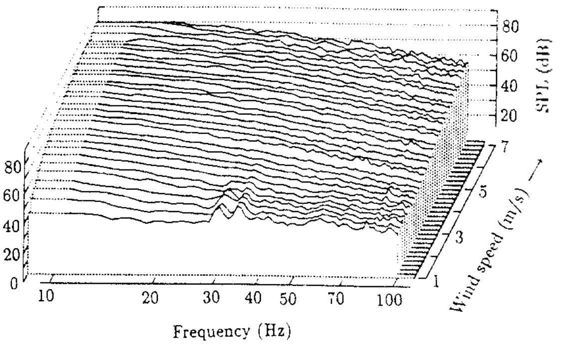

Fig. 4 The conditional average of power spectrum of the observed wind noise as the function of the wind speed from 1 to 7 m/s.

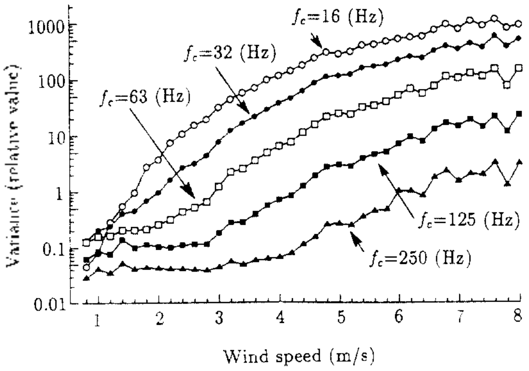

Fig. 5 Variance of the octave band wind noises as the function of the wind speed from 0.8 to 8 m/s.

The typical characteristics of the average power spectra $S_V(f, \alpha)$ in Eq. (3) are shown in Fig. 4. The proposed static estimation method can be applied by using this result. On the other hand, Fig. 5 shows the average variances V^b of octave band noises according to Eqs. (2) and (11). The proposed dynamic estimation method can be achieved by using these characteristics. Here, only the estimated results of the latent objective sound by using two types of static and dynamic methods are shown in Fig. 6 and 7. The effectiveness of two proposed methods can be seen from these results.

5. CONCLUSIONS

In the first, two static and dynamic types of the state estimation methods are newly proposed for the environmental problem on the low-frequency sound measurement in the presence of the wind-induced noise. These two kinds of estimation methods are theoretically discussed especially from the view point of positive use of the information on the wind speed. The effectiveness of the proposed methods are shown experimentally under the breezy condition in the open air.

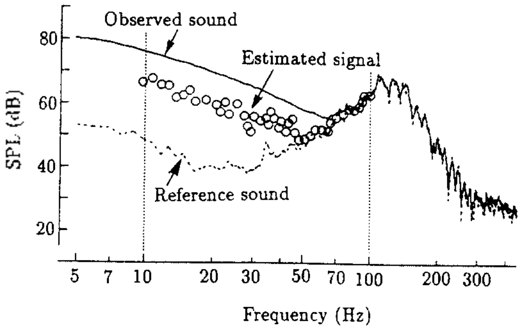

Fig. 6 An estimated results by using the proposed static method: average spectrum over the wind speed from 1.2 to 7 m/s, the observed sound and the reference sound observed under small wind noise are shown.

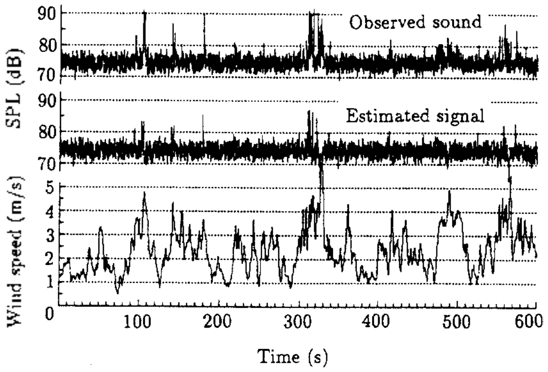

Fig. 7 An estimated results of objective sound by using the proposed dynamic estimation method: here only a trial for the constant level of the objective sound observed under the comparatively small wind speed is shown.

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