Development of Waterproof Low-frequency Windscreen with Extended Noise Reduction

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***Abstract*- As is often experienced, windnoise behaviour on the microphone seems somehow different from those following hydrodynamics or aeromechanics. Based on the preliminary investigation, prototype windscreen was developed for ultralow-frequency noise from wind-generated power facilities or heat-pomp water heater (EcoCute). The performance was discussed and examined from the concentrated viewpoints: (1) reduction of wind noise, (2) insertion loss and (3) water-proof/dew-condensation prevention capability, all about the outermost layer of the screen, as well as the possibility of extending the wind noise reduction by numerical or physical approach. The result implies items (1)-(3) deeply depend on the shape and material of the screen and, above all, the insertion loss on microphone mounting condition inside the screen as well. The new windscreen exhibits around 30 dB reduction below 1kHz, and insertion loss less than ±2dB in 1 Hz-20 kHz. Furthermore, in six-month observation on (3), water leak or dew condensation inside the screen was not found even under the local downpour of 30.5mm/h recorded in July 2010 at Miyazaki, Japan. Finally, numerical compensation by mounting two microphones inside and outside the windscreen, as well as physical approach of employing additional independent wind barrier, both indicated the possibility of additional 10-15dB (45 dB or more in total) reductions each.**

Keywords - Infrasound from Wind-generated Power Facility; Waterproof Windscreen; 0-dB Compensation

I. INTRODUCTION

According to the recent mass media report, various complains or problems are posed on the ultralow-frequency noise (infrasound) emitted from wind-generated power facilities and the like, such as health hazard, destruction of nature, etc. as in Table 1. The measurements of the infrasound are usually made in the open air, and then it is indispensable to consider the procedure for avoiding/reducing wind noise as well as waterproof/dew condensation prevention capability of sound pickup system. The authors here discuss and examine the performance of low-frequency windscreen as defined in the Standards (JIS or IEC) [3], i.e., as shown in the photograph above, from the viewpoints: (1) wind noise reduction, (2) insertion loss and (3) water-proof/dew-condensation prevention, all about the outermost layer composed of metal/fluorine porous materials, seeking for the possibility of further extending wind noise reduction by 10 dB or more.

TABLE I PROBLEMS AROUND WIND POWER GENERATION FACILITIES AND ACOUSTICAL ITEMS TO BE STUDIED AND SOLVED

(a)Comprehensive Issue	(b)Measurement Issue	(c)Windscreen (WS)	(d)WS structure
# Health Hazard (somnipathy/ psychological/ physiological) # Physical Hazard (rattling furniture/ bird strike) # Destruction of nature (deforestation/ habitat change) # Causal Research & Framing of Measures	# Parameter/Criteria # Measurement Point # Necessity of Disk /Diameter(Φ) # Method of avoiding /reducing wind noise (Need to extending the reduction by 15dB)	# Evaluation items: 1)Wind Noise 2)Insertion Loss 3)Waterproof/Dew-condensation Prevention 4)Portability/Electric Insulation	# Requisite items: 1)effectively blocks the air flow 2)causes no new swirling air flow 3)nonresonant materials for wind blocking layer

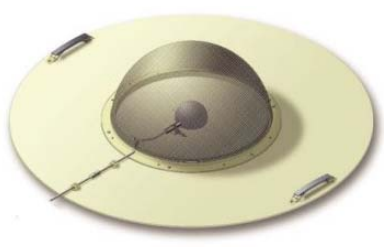


Fig. 1 Configuration of typical low-frequency windscreen

In contrast with atmospheric wind-generated noise reducer systems recently developed to promote the infrasound network of the International Monitoring System (IMS) for the enforcement of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) such as those using low impedance elements [1] or improved rosette infrasonic noise-reducing spatial filters [2], where the maximal noise reduction 15-20 dB is obtained at 0.02-7 Hz with flat frequency response up to 4 Hz, the new system described in this paper is mainly aiming at windnoise reduction in low-frequency sound from wind-generated power facilities toward the final goal of windnoise reduction around 30 dB at higher frequencies than 10 Hz, or even 45 dB with additional extension by physical or numerical approach, associated with flat frequency response at 1.0-16 kHz.

II. GROUND SURFACE PRESSURE AND THE WIND NOISE

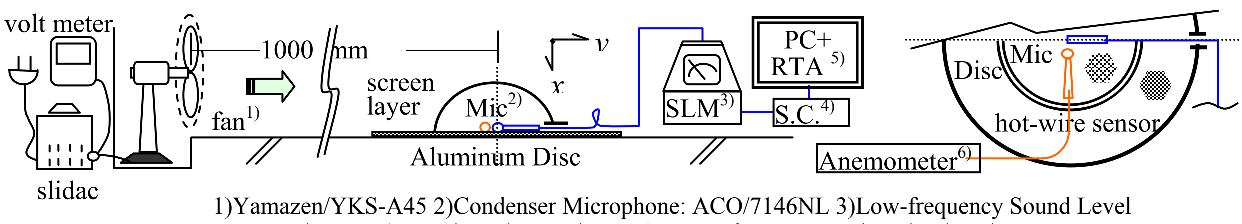
Apart from the imission measurement, hereafter ultralow-frequency noise power emitted from wind-generated power facilities will be discussed.

A. Estimation of Ground Surface Pressure

In contrast to indoor measurement for health hazard assessment, the measurements of infra-noise from wind-generated power facilities are usually made at specified outdoor points to observe the total noise power emitted from the facilities. Squared pressure $|p|^2$ on the rigid wall (x=0 in Fig. 2) for the incoming sound with incident angle θ is written as follows, taking the reflected wave into account [4]:

$$p_i = p_0 \exp[-ik(x \cdot \cos\theta + y \cdot \sin\theta)], \quad k \equiv \omega / c \tag{1}$$

$$<\left|p^2\right|>= 2p_0^2[1+\cos(2\mathrm{kx}\cdot\cos\theta)] \xrightarrow{\mathrm{x}=0} 4p_0^2 \tag{2}$$



1)Yamazen/YKS-A45 2)Condenser Microphone: ACO/7146NL 3)Low-frequency Sound Level Meter :ACO/6238L 4)Sound Card :ACO/8833 5)RTA software :Sound Technology/SpectraPLUS Pro 6)Hot-wire Anemometer: Kanomax Japan/MODEL6511

Fig. 2 Setup for estimating wind noise reduction under various windscreen conditions

Also, it can be rewritten as $\langle|p|^2\rangle$ in Eq. (3) for random incidence of sound by averaging on θ:

$$<\left|p^2\right|>= 2p_0^2[1+\sin(2kx)/(2kx)] \xrightarrow{\mathrm{x}=\infty} 4p_0^2 \tag{3}$$

Simply, it is increased by 6 dB on the wall for the incident noise, as well as by 3 dB for the noise pressure at infinite distance under the condition of random incidence as $|p_\infty|^2 \equiv 2p_0^2$. Frequency responses are both flat free from phase rotation, which can be observed by measuring surface pressure with pressure type microphone. This holds for the case of geomorphic measurement of infrasound from wind-generated power facilities.

B. Wind Speed Above the Ground

Meanwhile, wind speed V_x is increased with distance from the ground surface, x, as in Eq (4):

$$V_x = V_h (h / x)^{1/n} \quad (\mathrm{m/s,\ n = 7\ for\ field\ of\ grass}) \tag{4}$$

which then, for wind speed V_h=10 m/s at reference height h=30m, for instance, leads to V_x=6 m/s at x=1m, minimum value very close to the ground [5]. Eventually, in the measurement of infrasound, the observation of ground surface pressure seems reasonable and most advantageous from each viewpoint S/N, frequency response and wind noise as stated in the Standards [3].

C. Wind Speed Above the Ground

In consideration of these situations stated above, prototype windscreen was developed through lengthy cut-and-try procedure, the performance was evaluated in the system shown in Fig. 2 by employing blower fan as wind source. The results are shown in Fig. 3 where wind noise (Leq (dB) for 30 sec) is monotonically increased with wind speed v(m/s) in each frequency with peak-frequency shifted to higher frequency, and is decreased to a considerable degree with the screen as in (b), definitely revealing fan noise in circle #P as "target noise" at middle frequencies, which was entirely masked by wind noise as in (a). It should thus be carefully noted, in the evaluation of windscreen with large wind noise reduction, that background noise and/or wind source (fan) noise should be put down together.

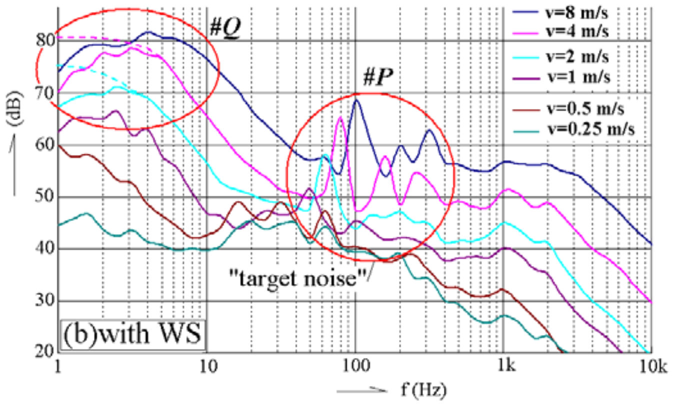


Fig. 3 Wind noise under various wind speeds *v*(m/s), (b)with and (a)without windscreen (WS)

III. WIND NOISE REDUCTION

A. Requirement for Wind Noise Reduction

In Fig. 3 (b), dotted lines in circle #*Q* refer to the data measured under outdoor natural wind condition, which increases monotonically toward low frequencies unlike those with artificial winds (fan). The measurement was made using the blower fan as in Fig. 2, though, considering the distinction above is neither significant nor influential on the difference of (a) and (b), i.e. on the degree of the wind noise reduction. Since wind noise can arise not only from (a) swirling air current caused by the existence of the microphone itself, but (b) fluctuation of negative pressure due to the air flow passing above the microphone diaphragm or (c) noise of wind itself, it is no use embedding pressure type microphone onto the ground so that the diaphragm falls in plane with the ground surface, which significantly implies the need of physical or numerical approach to suppress the influence of the wind noise, such as windscreen or noise compensation technology [6].

To establish an effective performance of the windscreen, requirements should be fulfilled that: (1) the outmost windbreak layer of the screen effectively blocks the invading wind, (2) but does not engender another air turbulence and (3) the windbreak layer does not resonate itself.

B. Final Configuration of the Windscreen

Based on the requirements above, the ultimate structure of the new windscreen was determined as in Fig. 4 through a lengthy try-and-error procedure. The wind speed observed inside the screen is 0.1 m/s or less as in Fig. 5, implying the fulfilment of the requirements (1)-(3). Incidentally, the increase of the number of screen layers or easy addition of sound absorber inside the screen did not exhibit significant improvement.

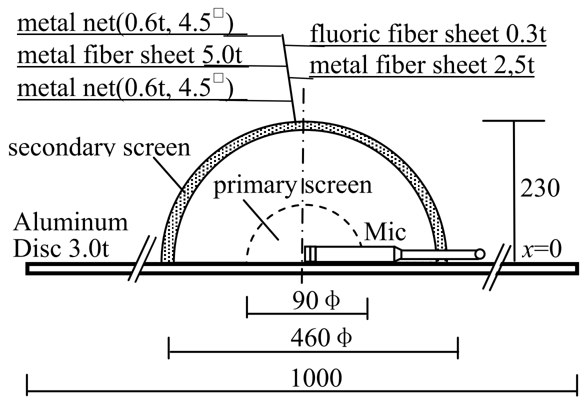


Fig. 4 Basic structure of new waterproof windscreen

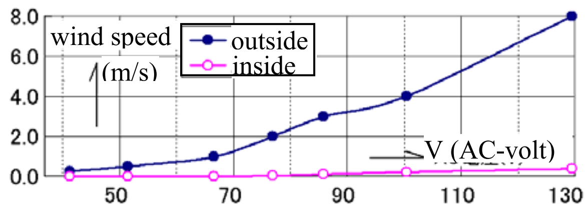


Fig. 5 Wind speed inside and outside the screen

IV. EXAMINATION OF INSERTION LOSS △(DB)

Insertion loss △(dB), level difference between responses of the microphone to the speaker with and without windscreen, is the second major requirement to be fulfilled, which relates to the material and structure of the screen as well as to mounting condition of the microphone. The speaker was placed in an anechoic room as in Fig. 6 with vertical angle θ and distance 1 m apart from the microphone mounted on the disc under various conditions (1)-(6) using electret condenser microphone (ECM) or silicon microphone as in Fig. 7.

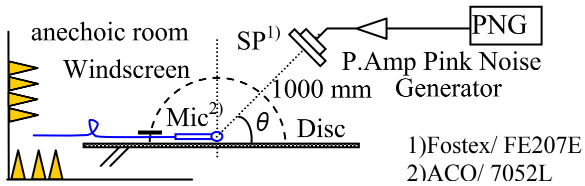


Fig. 6 Measurement of insertion loss △(dB)

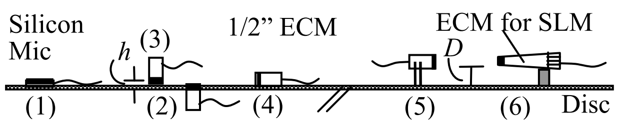


Fig. 7 Various conditions of microphone setting

Fig. 8 shows the result of △(dB) investigation in Leq for 30 sec, obtained with pink noise. In contrast with arrangement Mic(4) with fluctuation within ±2dB, Mic(5) and (6) exceeds ±4dB definitely implying the microphone should be mounted directly on the disk (d=h=0), and that conditions (5) and (6) bring about enormous fluctuation both at low and high frequencies. Thus, it is recommended to use silicon microphone as in (1) or to place ECM directly on the disk as in (2)-(4).

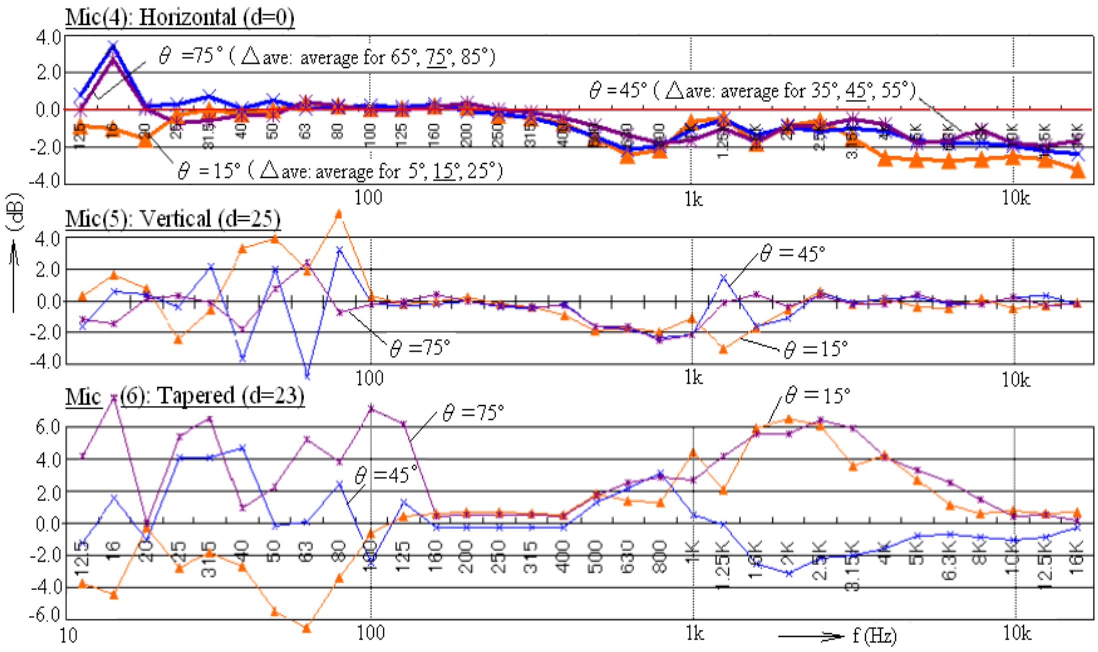


Fig. 8 Insertion loss △(dB) for incident angle θ=15°, 45° and 75°, each shown with energy average of 3 adjacent angles

V. WATER PROOF AND DEW CONDENSATION PREVENTION PROPERTY

In long-term outdoor measurements of infrasound, waterproof property and dew condensation prevention capability are the key factors of windscreen, as well as electric insulation of the disc surface is indispensable in direct mounting scheme of ECM onto the disc (d=h=0). In the prototype windscreen shown in Fig. 4, the spaces inside and outside the screen are connected thermally by the aluminium disc but isolated by metal/fluorine sheet as heat insulating layer, fulfilling the basic condition for avoiding dew condensation. In particular, fluorine sheet with thickness 300 µm at the outmost layer seems to play a significant role in avoiding dew condensation. In six-month morning observation since August 2011, either water leak or dew condensation was not found inside the screen as illustrated in Fig. 9, even in the local downpour of precipitation 30.5 mm/h recorded at Miyazaki prefecture, Japan.

Fig. 9 Dew drops seen around the new windscreen

TABLE II IMAGE OF THE "V-N TABLE" TO OBTAIN THE TARGET, V(M/S) AND $\overline{n_1^2(t)}$, FROM THE ARGUMENT $a\overline{N_1^2(t)}-\overline{n_1^2(t)}$

v=5.0(m/s):Voltage on blower fan V=77.67(AC-volt)			Result 2							
No.	Parameters	Frequency(Hz)	1.00	1.25	1.60	2.00	2.50	3.15	4.00	5.00
[1]	$v(\mathrm{m/s})\rightarrow a\overline{N^2(\mathrm{t})}$	: $a\cdot\overline{S_1^2(\mathrm{t})}$ at $\overline{s_1^2(\mathrm{t})}\approx 0$	92.45	85.22	Result 1					95.87
[2]	$\overline{n^2(t)}$	: $a\cdot\overline{S_1^2(\mathrm{t})}$ at $\overline{s_1^2(\mathrm{t})}\approx 0$	80.12	69.00	60.99	58.95	63.63	60.32	60.56	60.5[illegible]
[3]	$q = a\overline{N^2(t)}-\overline{n^2(t)}$	: [1]−[2]	92.19	85.12	Argument					95.8[illegible]
[4]	$q = a\overline{N^2(t)}/\overline{n^2(t)}$	: [1]−[2] in dB	12.33	16.22	21.63	26.50	21.80	27.44	32.12	35.32

VI. FURTHER EXTENTION OF WIND NOISE REDUCTION

A. Numerical Approach: Compensation by Predicting the Wind Speed

Based on the assumption that outdoor natural wind blows almost in the horizontal plane in a grass field and that wind noise increases monotonically with wind speed v(m/s) as suggested in Fig. 3, it is possible to estimate v and RMS wind noise inside the screen $\overline{n^2(\mathrm{t})}$ by processing outputs of two omni-directional microphones, S_1(t) and S_0(t), each mounted on the central axis inside and outside the screen as illustrated in Fig. 10 to pick up the surface pressure on the screen and the disc, expecting the wind noise on outer microphone $\overline{N^2(\mathrm{t})}$ to depend only v, not on wind direction φ:

$$\text{Inner Mic}: \quad \overline{S_1^2(\mathrm{t})} \quad \overline{s_1^2(\mathrm{t})}+\overline{n^2(\mathrm{t})} \tag{5}$$

$$\text{Outer Mic}: \quad \overline{S_0^2(\mathrm{t})} \quad \overline{s_0^2(\mathrm{t})}+\overline{N^2(\mathrm{t})} \tag{6}$$

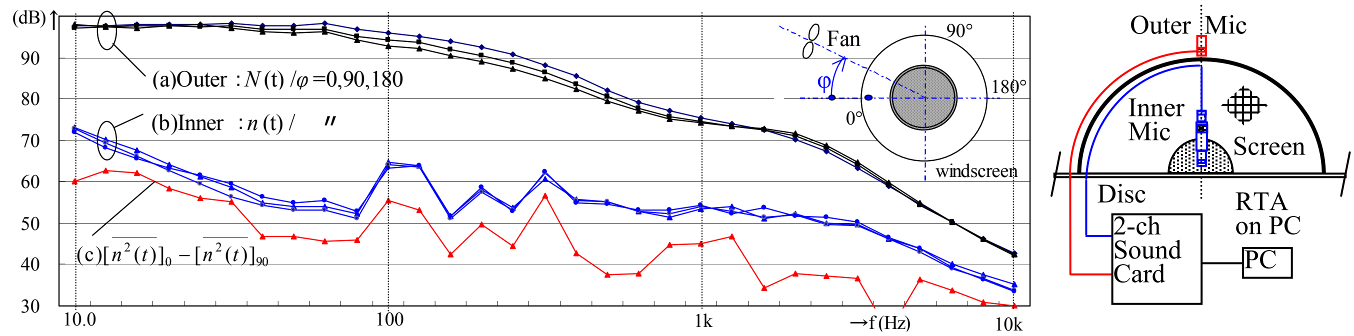


Fig. 10 Wind noise observed (a) outside and (b) inside the screen, shown with residual noise (c) compensated

First step is to measure pure wind noise $\overline{\mathrm{n}^2(\mathrm{t})}$ and $\overline{\mathrm{N}^2(\mathrm{t})}$, at various wind speeds v under quiet condition(target noise $s_1(t)=s_0(t)\approx 0$ to establish "v-n Table" as in Table 2, all to obtain v and $\overline{n^2(\mathrm{t})}$ from argument $a\cdot\overline{N^2(\mathrm{t})}-\overline{n^2(\mathrm{t})}$ instead of $\overline{N^2(\mathrm{t})}$ since the outer microphone, in the actual measurement, could include the target noise $s_0(t)$ as "error source" for estimating v and $\overline{n^2(\mathrm{t})}$, where a is factor to compensate the insertion loss ⊿(dB) and microphone sensitivities so that:

$$a\cdot\overline{s_0^2(\mathrm{t})}=\overline{s_1^2(\mathrm{t})}\equiv\overline{s^2(t)} \tag{7}$$

In the actual measurement, argument $a\cdot\overline{N^2(\mathrm{t})}-\overline{n^2(\mathrm{t})}$ of "v-n Table" is obtained by performing Eq.(8) to cancel out the term $\overline{s_1^2(\mathrm{t})}$ and $\overline{s_0^2(\mathrm{t})}$, where incidentally wind noise is to be decreased by 1/q as Eq.(9):

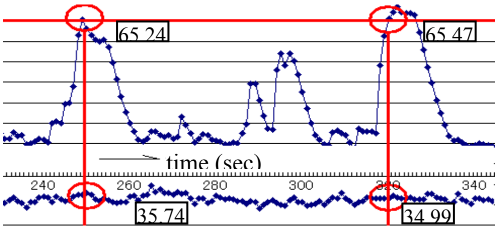
$$(6)\times\mathrm{a}-(5): \; a\cdot\overline{S_0^2(\mathrm{t})}-\overline{S_1^2(\mathrm{t})}=a\cdot\overline{N^2(\mathrm{t})}-\overline{n^2(\mathrm{t})} \tag{8}$$

$$\overline{n^2(\mathrm{t})} = a \cdot \overline{N^2(\mathrm{t})} / q \tag{9}$$

Finally, the target $\overline{s_1^2(\mathrm{t})} \equiv \overline{s^2(t)}$ is worked out as follows from $\overline{n^2(\mathrm{t})}$ obtained in “*v-n* Table” [5]:

$$\begin{aligned} \overline{S_1^2(\mathrm{t})} - \overline{n^2(\mathrm{t})} &= \frac{1}{T}\int_0^T [S_1^2(t)]dt - \overline{n^2(t)} \\ &= \frac{1}{T}\int_0^T [s_1^2(t) + 2s_1(t)n(t) + n^2(t) - \overline{n^2(t)}]dx \\ &\xrightarrow{s_1(t)n(t)\to 0,\ n^2(t)-\overline{n^2(\mathrm{t})}\to 0} (1/T)\int_0^T s^2(x)dx = \overline{s_1^2(t)} \end{aligned} \tag{10}$$

where the second term converges to zero in the integration of the product of orthogonal functions as well as the third and fourth terms are balanced out [6]. Figure 10 shows $\overline{N^2(\mathrm{t})}$ and $\overline{n^2(\mathrm{t})}$ measured at different angles of wind source (blower fan), Φ =0, 90, 180°, which both seem to coincide each other resulting in smaller difference of $\overline{n^2(\mathrm{t})}$ by 10-15 dB than original $\overline{n^2(\mathrm{t})}$ itself as illustrated with red line as residual noise of the compensation, implying the validity of the assumption and the possibility of extending the reduction. The same holds for the case of natural wind, confirmed in 24-hour outdoor observation as in Fig. 11. The wind noises of outer microphone $\overline{N^2(\mathrm{t})}$ sampled at random around 65 dB seem to well correspond to constant level of $\overline{n^2(\mathrm{t})}$ with constant difference around 30.0 dB. Incidentally, anemometer established as above is expected omni-directional and to have faster response than conventional ones.



Time(s)	(1)Outer	(2)Inner	(1)-(2)
249	65.2	35.7	29.5
320	65.5	35.0	30.5
436	64.6	34.4	30.2
758	65.3	35.1	30.2
836	64.6	33.8	30.8
3095	65.0	35.3	29.7

(dB)

Fig. 11 Comparison of natural wind noises on inner and outer microphones sampled at random

B. Physical Approach: Addition of Independent Wind Barrier

The other possibility of extending the reduction is to establish the independent wind-blocking barrier in front of (outside) the original screen. As often experienced, it is no use vainly increasing the number of layers of the screen. The extension is possible only by constructing “the third wind-blocking layer” in conformity to the requirement: (1) employment of completely sound-through and almost wind-through barrier structure, (2) different configurations of the barrier from the original screen, (3) mounting the new layer directly on the ground (not on the disc) and (4) tilting the layer slightly backward (not perpendicular to the wind).

Figure12 shows the results of the same experiment using two microphones as in Section A, where (b) custom-built double metal net or (c) glass-fiber board sandwiched in between the nets was placed each in front of the original screen and directly on the ground. Wind noise is effectively decreased with (b) at both inside and outside the screen, but somehow limited with (c) even considering the fan noise masking the wind noise at frequencies higher than 100 Hz, which implies the occurrence of new swirling of air with (c) although fiber glass seems to better block the wind. Without the fan noise, the noise reduction in inner microphone with (b) would approach the result of outer microphone. Incidentally, it is interesting (b) came to wind-through structure for the best wind noise reduction. The experiment verifies the validity of the above-mentioned requirements as well as a possibility of establishing optional devices as shown in Fig. 12 (1)-(3), to be put on over the original windscreen to extend the reduction by another 10-15 dB as implied by additional wind-blocking material (b).

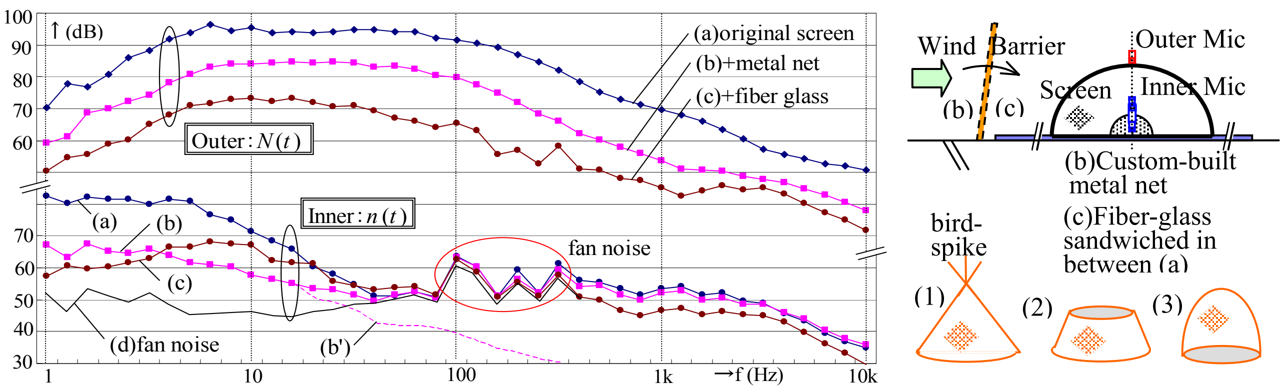


Fig. 12 Wind noise reduction by optional wind-blocking layer (b) or (c) as well as (1)-(3), derivatives of (b)

VII. CONCLUSIONS

Finally, the outer screen composed of (b) custom-built double metal net came out as in Fig. 13. Then, totally, the microphone wind noise for infrasound measurement is expected to be reduced by around 50 dB at major frequencies including ultra-low frequencies as illustrated in Fig. 14 (b') by employing the wind screen with fluorine/metal layer, associated with extra numerical compensation approach using two microphones inside and outside the screen, or with physical approach of employing additional independent wind barrier composed of "wind-through" custom-built metal net as in Fig. 13, both offering a possibility of additional 10-15dB reductions each.

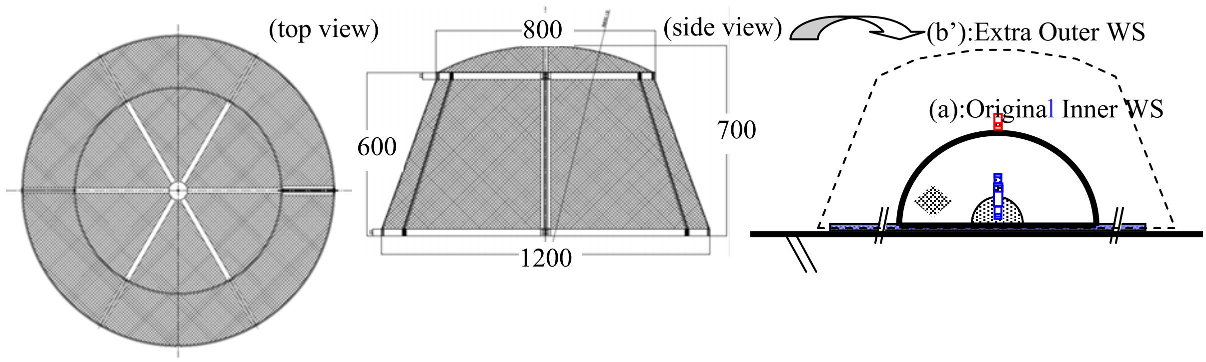


Fig. 13 Prototype outer WS to be crowned over the original so as to meet (1)-(4) and folded up for transportation, extending R(dB) by 10-15 (dB)

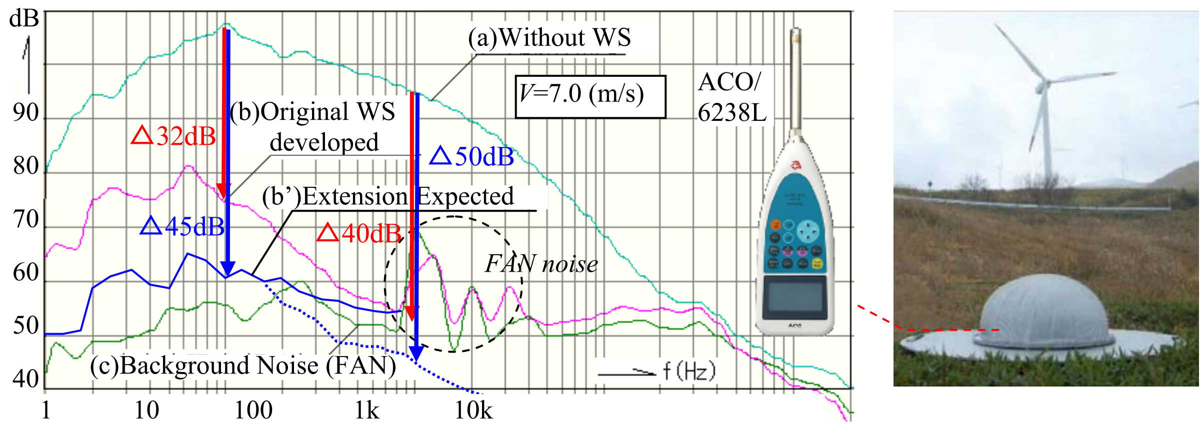


Fig. 14 Wind noise reduction by prototype windscreen (b), shown with (c) fan motor noise around 100 Hz and (b') extended reduction obtained with the custom-built metal net discussed in Fig. 12 (b)

From the fundamental investigation made in advance, it turned out the newly developed low-frequency windscreen fulfils the basic requirements (1) wind noise reduction, (2) insertion loss and (3) water-proof/dew-condensation prevention capability, each of which deeply depends on the shape and materials of the outmost layer of the screen, while the insertion loss mainly on mounting condition of the microphone as well. The prototype windscreen exhibits approximately 30 dB of reduction by itself at lower than 1kHz, and insertion loss less than ±2dB in the range 1 Hz to 20 kHz without water leak or dew condensation inside the screen during six-month long-term observation.

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