Experimental study of meteorological and ground effects on outdoor sound propagation for developing aircraft noise prediction model

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ABSTRACT

JAXA has been developing an aircraft noise propagation model by applying the GF-PE method. To predict aircraft noise propagation precisely, it is necessary to assume meteorological condition and ground property in the sound field appropriately. In order to study how to model those conditions in the predictions and to verify the model, outdoor sound propagation experiments were conducted in November 2012 and in July 2013 at Taiki Aerospace Research Field in Hokkaido, Japan. In the experiments, receivers were lined up on the 1000-meter long runway and on the grass-covered flat ground in the test field. An elevated sound source was hanged from a tethered balloon, while other sound sources were placed at ground level. Air-to-Ground and Ground-to-Ground impulse responses were measured under various meteorological conditions. In this paper, we introduce variations in excess attenuation due to the meteorological and ground effects. By comparing the experimental results and the calculation results of the GF-PE method, we also discuss appropriateness of the modeling of meteorological conditions and ground property in the developing aircraft noise prediction model.

Keywords: Aircraft noise, Meteorological effect, GF-PE
I-INCE Classification of Subjects Number(s): 24.6,24.9

1. INTRODUCTION

Long-range outdoor sound propagation is considerably affected by atmospheric condition such as vertical profiles of wind speed and temperature. Propagation of aircraft noise is one of the representative examples of long-range sound propagation in daily living environment, and noise exposure around an airport varies with meteorological condition. In order to manage aircraft noise exposure, Japan Aerospace Exploration Agency (JAXA) is conducting a research on a flight path optimization with consideration of meteorological conditions (1). As one of the key functions in the path optimization, it is necessary to develop a precise aircraft noise prediction model which enables to take account of the meteorological effects on the noise propagation. Two propagation models are being developed. One is precise numerical computation based on a Green's Function Parabolic Equation (GF-PE) method to predict outdoor sound propagation in an arbitrary meteorological condition. The other is based on a table-lookup technique for the real-time path optimization which refers to a database of the corrections for meteorological effects on sound propagation previously computed by GF-PE under typical meteorological conditions(2).

To confirm the applicability of the propagation models and to improve them, precise experimental data of Air-to-Ground sound propagation under various meteorological conditions are absolutely essential. In November 2012, we conducted a series of impulse response measurements from an elevated sound source to receivers at ground level under several meteorological conditions (3). The meteorological effects on Air-to-Ground sound propagation have been investigated based on the

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results of the controlled experiments avoiding uncertainty of sound power level of the source.

In this study, another series of impulse response measurements from an elevated sound source to receivers at ground level was conducted once again in July 2013. The meteorological effects on Air-to-Ground sound propagation have been investigated based on the results of the both experiments conducted in 2012 and in 2013. This paper first presents outline of the series of field experiments. Then the experimental results are investigated to discuss meteorological and ground effects on outdoor sound propagation. The results of the measurement and the GF-PE calculation are compared to discuss the accuracy of the calculation method.

2. OUTLINE OF FIELD EXPERIMENTS

Two series of field experiments were conducted at Taiki Aerospace Research Field in Hokkaido Japan in November 2012 (Exp-1) and in July 2013 (Exp-2). In the field, there was an asphalt concrete runway with a length of 1000 m. Impulse responses from an elevated source in the air to receivers at ground level (AtoG) were measured by using time stretched pulse (TSP) method. In addition, impulse responses from a source set at ground level to receivers at ground level (GtoG) were also measured.

2.1 Experimental Setup

Figure 1 shows the layout of the test field. For the experiments on AtoG sound propagation, an omnidirectional loudspeaker was set at a height of 100 m, 300 m or 500 m above ground by hanging from a tethered balloon (3). The balloon was tethered to a winch set around the center of the runway (S_c) or around the west side of the runway end (S_W). The precise source position was recorded by a GPS tracking system mounted on the balloon. Loudspeakers for the experiments on GtoG sound propagation were set at 1.2 m in height at the positions shown in Fig. 1. The receivers were lined up at intervals of 100 m on the runway and on the grass field parallel to the runway.

In conjunction with the sound propagation experiments, meteorological conditions (wind speed, wind direction, temperature, humidity, and atmospheric pressure) were observed continuously at several points shown in Fig. 1. Upper-air observations were also carried out by radiosondes, Doppler sodars and Lidar.

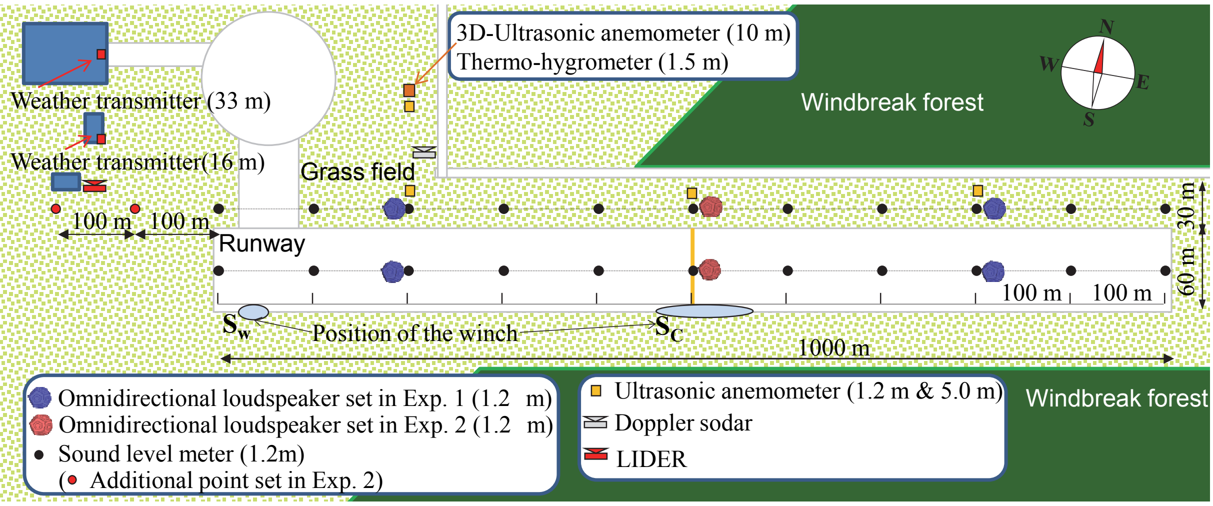


Figure 1 – Layout of the measurement field

(*notes in parentheses indicate the height of the apparatuses)

2.2 Conditions during Experiments

Table 1 shows the number of impulse response measurements on AtoG sound propagation conducted by setting the source at each position and height. Table 2 also shows the number of impulse response measurements on AtoG sound propagation classified by meteorological categories. In the table, atmospheric stability condition is determined based on the difference in potential temperatures observed at 16 m in height and at 33 m in height.

Table 1 – The number of impulse response measurements on Ar-to-Gound sound propagation

Source position \ Source height	100 m	300 m	500 m
at around Runway Center (S_c)	28	44	42
at around West side of Runway End (S_W)	85	130	75

Table 2 – The number of impulse response measurements* on Ar-to-Ground sound propagation

Stability \ wind speed category	W1	W2	W3	W4	W5
	0 to 1 m/s	1 to 3 m/s	3 to 6 m/s	6 to 10 m/s	> 10 m/s
Stable	11 (5/6)	51 (41/10)	2 (0/2)	0 (0/0)	0 (0/0)
Nutural	2 (0/2)	55 (17/38)	66 (7/59)	0 (0/0)	0 (0/0)
Unstable	2 (0/2)	101 (0/101)	114 (0/114)	0 (0/0)	0 (0/0)

*(the number of measurements during Exp-1 / Exp-2)

2.3 Procedure

Impulse response measurements on AtoG sound propagation were repeated five times in a trial. Then a trial on GtoG sound propagation was carried out after the trial on AtoG sound propagation with a short time interval. In the experiments, the sets of the trial on AtoG sound propagation and GtoG sound propagation were conducted repeatedly by changing source height at 100 m, 300 m or 500 m. In some cases, however, the impulse response measurements were not able to be conducted five times in a trial because of the shortage of the operation time.

In order to examine AtoG sound propagation in opposite direction at a time, namely eastbound (W→E) and westbound (E→W), the source was set at the position S_c. On the other hand, the source position S_w was selected when the measurement focused on examining long-range AtoG sound propagation. As for GtoG propagation, Exp-1 aimed to examine sound propagation in the opposite directions and two sets of sound sources were set at 300 m west and 300 m east. In Exp-2, the loudspeakers were set at the center to examine sound propagation in both east and west direction at a time.

3. Results and Discussion

3.1 Difference in Sound Exposure Level under Different Ground Conditions

Figure 2 shows an example of sound exposure level at each receiving point obtained in each condition of source height at 100 m, 300 m, and 500 m. In the figure, the horizontal axis shows the distance from a sound source to each receiver and the Fresnel number calculated as Eq. 1. The vertical axis shows sound pressure level (SPL) relative to the band power level of the source. Each plot shows arithmetic average of sound exposure level calculated from five impulse responses obtained in a trial, and the error bar means its standard deviation.

$$\mathrm{N} = 2 \cdot \delta / \lambda \qquad (1)$$

where N is the Fresnel number, δ is the path length difference ($l_r - l_d$) [m], l_d is the length of the direct propagation path from a source to a receiver [m], l_r is the length of a ground reflection path (length of the path from a source to the mirror-image receiver) [m], and λ is the wave length [m] calculated by assuming the sound speed is 340 m/s.

It is clearly seen that difference in SPL due to the difference in ground condition is small in cases where the frequency is high or the source height is high. It is also found that the differences are large in the conditions that the Fresnel number is below 1.

Figure 3 shows relationship between excess attenuation and angle of elevation obtained from the results in Exp-2. In the figure, the black and the blue lines show the results obtained at the receiving points on the runway and on the grass field, respectively. Each plot indicates the arithmetic average of excess attenuation obtained in each elevation angle condition and the error bar shows its standard deviation. Clear differences can be seen in conditions that the Fresnel number is below 1. In 1 kHz octave band, some level differences are seen in almost all elevation angle conditions in which the Fresnel number is always above 1. It is found however that the level differences are comparable to the variation in excess attenuation due to meteorological effects indicated as the standard deviation.

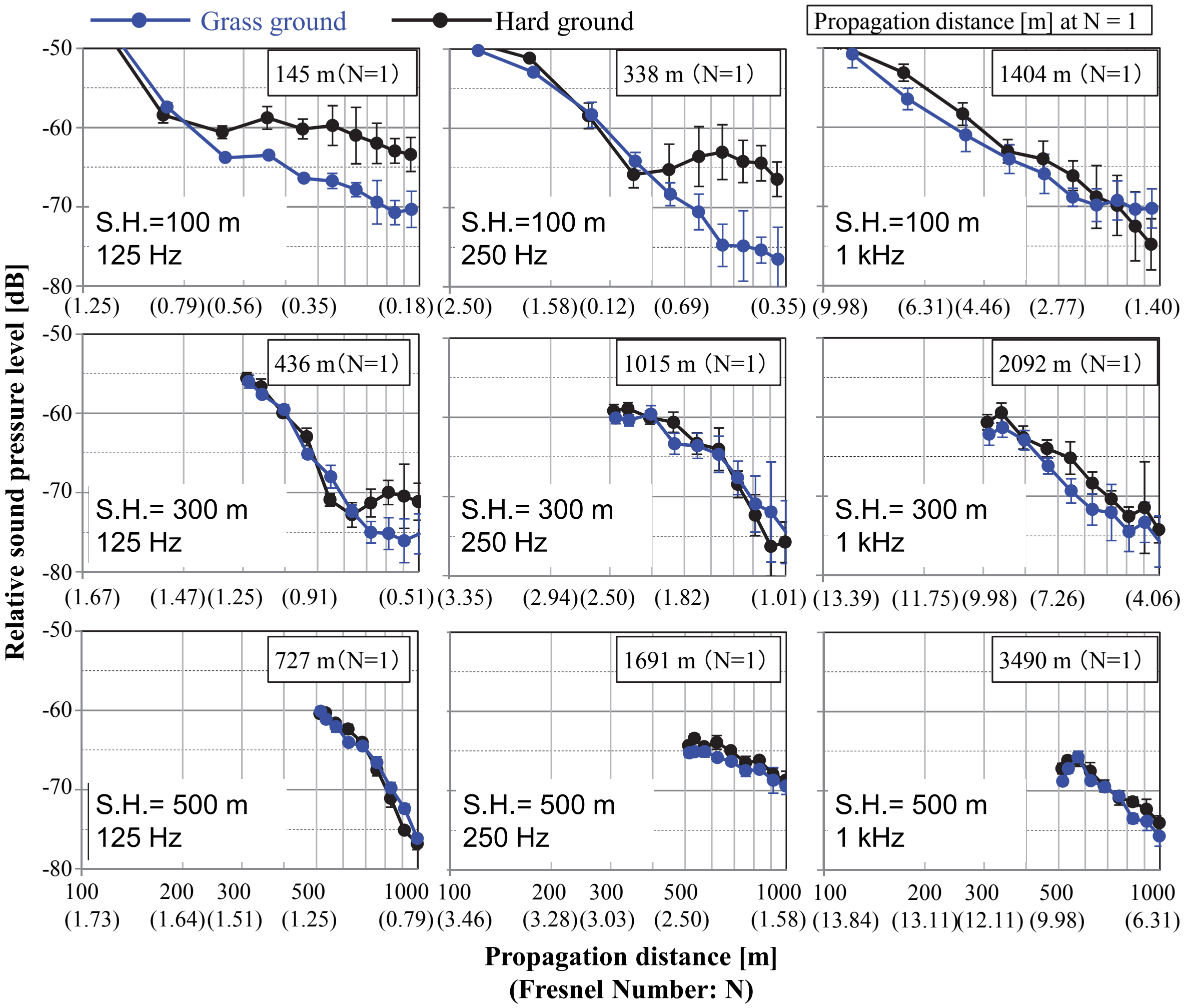


Figure 2 – Octave band sound exposure level obtained at each receiving point

(Top: Source height (S.H.) = 100 m, Middle: S.H. = 300 m, Bottom: S.H. = 500 m)

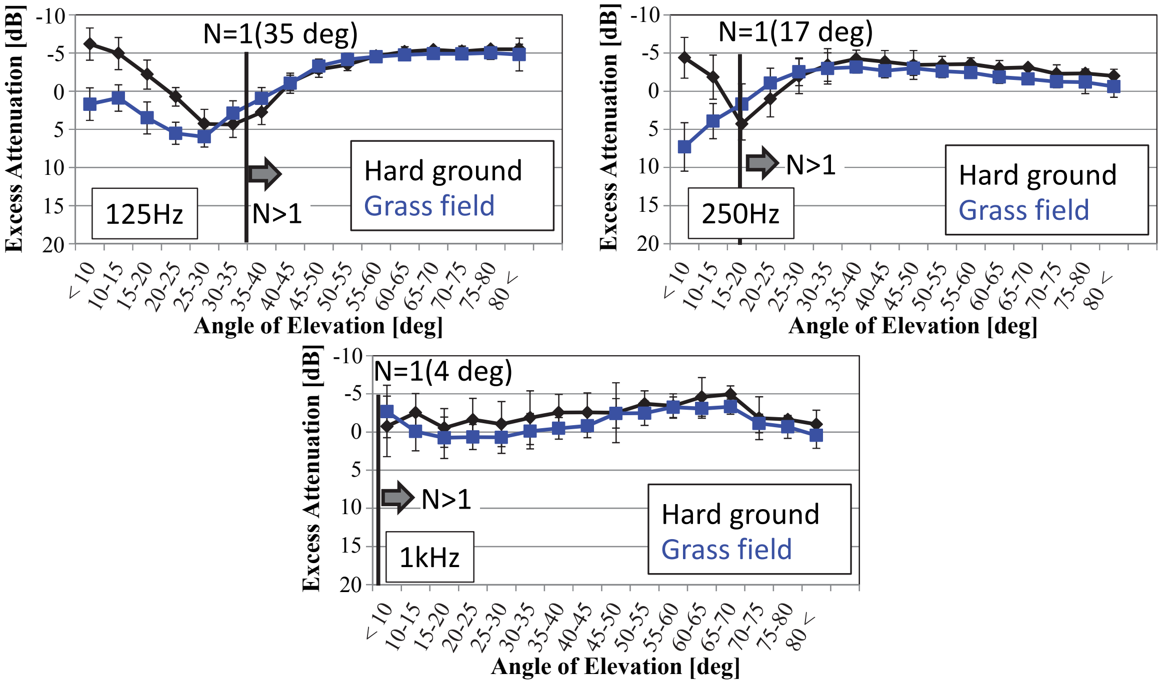


Figure 3 – Differences in ground effects

3.2 Variations due to Meteorological Effects

Figure 4 shows excess attenuation in 1 kHz octave band obtained at each receiving point set on the runway. In each graph, the horizontal axis means the direct propagation distance from the source to each receiving point which is categorized into every 100 m and the vertical axis means the excess attenuation. Each plot means the arithmetic average of excess attenuation at each distance calculated for every vector wind speed category (v.w.s). In this study, the vector wind speed category was determined based on the 1-minute averaged wind speed observed by an ultra-sonic anemometer set near the runway at 5 m in height. In cases of AtoG sound propagation, the 90 % range of the excess attenuation obtained at each distance is also indicated by gray bar. It is clearly seen that excess attenuation on AtoG sound propagation (S.H. > 100 m) is fluctuated due to meteorological effects and the variation seems to be regardless of vector wind speed near ground. It is considered that the fluctuations might be occurred due to the atmospheric turbulence effects and/or the difference in wind conditions near ground and at higher altitude. It is also found that the range of the variation becomes smaller with the source height becomes higher.

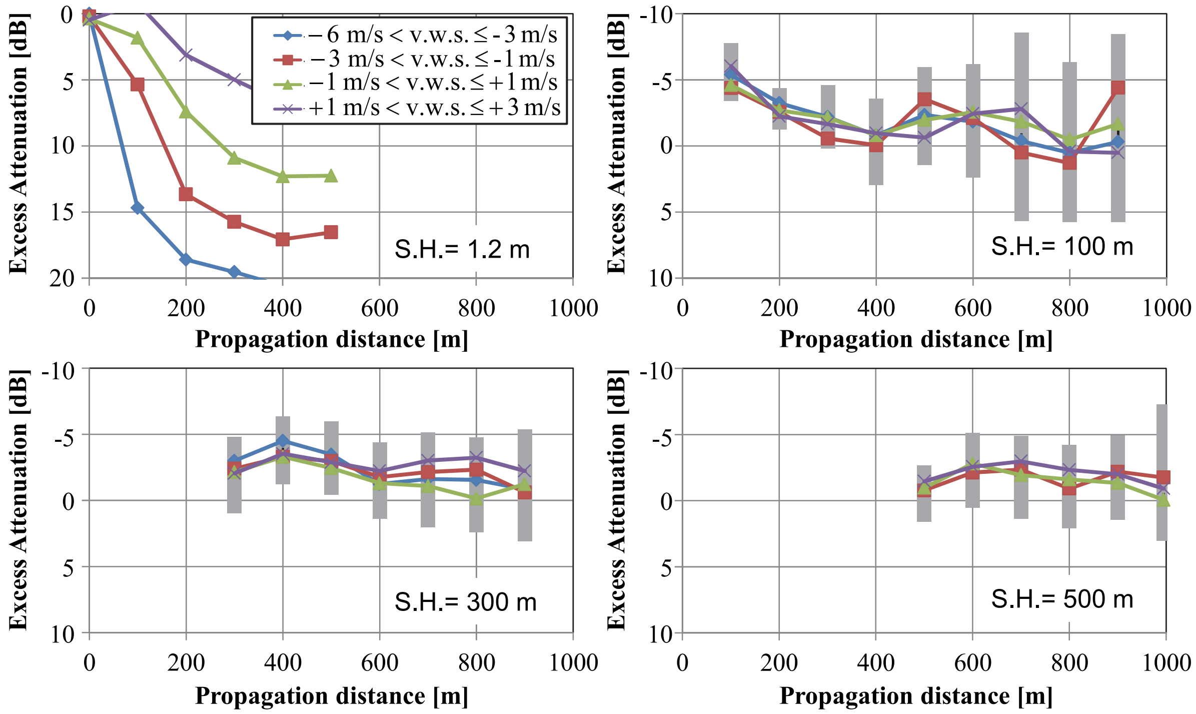


Figure 4 – Variation in excess attenuation in 1 kHz octave band obtained at the receiving points on hard ground

3.3 Comparisons between Experiments and Calculations

GF-PE calculations have been conducted with effective sound speed profiles estimated based on the observed meteorological data during the experiments. Atmospheric turbulent effects have been also taken into account by assuming an atmosphere with a von Kármán spectrum of refractive-index fluctuations. The profiles of effective sound speed and the structure parameters in von Kármán spectrum on the fluctuations of temperature and wind speed are assumed as described in reference (3). A wind speed profile has been assumed by dividing into two layers, that is, the lower layer up to 100 m in height and the upper layer. In both layers, the vector wind profiles have been assumed to be logarithmic. The lower vector wind speed profile has been estimated using the vector wind speed observed at 5 m in height. Then the upper profile has been estimated using the vector wind speed at 100 m in height of the resultant lower profile. The temperature profile has been estimated by interpolating the observation results of radiosonde carried out several times a day. The structure parameters on the fluctuations of temperature and wind speed have been set based on the standard deviation of observed temperature and wind speed.

Figure 5 shows an example of comparisons of excess attenuation between experiments and calculations. In each graph, two kinds of results obtained in different meteorological conditions are plotted. The results indicated by open circles were obtained under the stable atmosphere with vector wind speed of +1.0 m/s, whereas the results indicated by closed circles were obtained under unstable atmosphere with vector wind speed of -3.8 m/s. Each plot indicates arithmetic average calculated from excess attenuation of five impulse responses measured (red line) or calculated (blue line) in a trial and the error bar indicates its standard deviation. Gray line shows the analytical results calculated assuming a homogeneous atmosphere. It can be seen that excess attenuation obtained by the measurements in each meteorological condition does not correspond that of analytical results due to meteorological effects, except for the case of 125 Hz. On the other hand, the GF-PE calculation results are in relatively good agreement with measurement results, and they represent the variation in excess attenuation measured in different meteorological conditions. In the measurements in Exp-2, the minima of excess attenuation caused by the interference between the direct sound and a ground reflection is occurred in 500 Hz octave band, in which it was shifted from the range about 800 m to about 600 m due to the meteorological effects. It can be seen that the GF-PE calculations represents the shift of the minima, precisely.

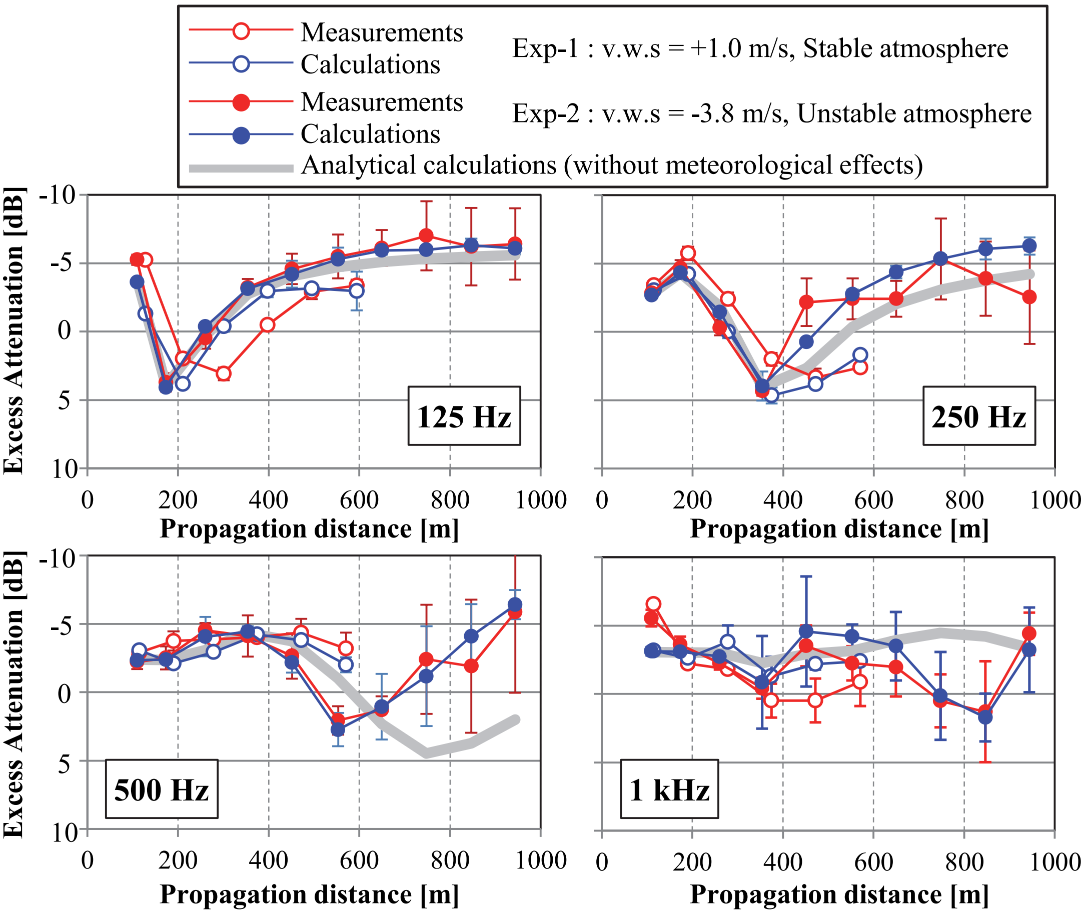
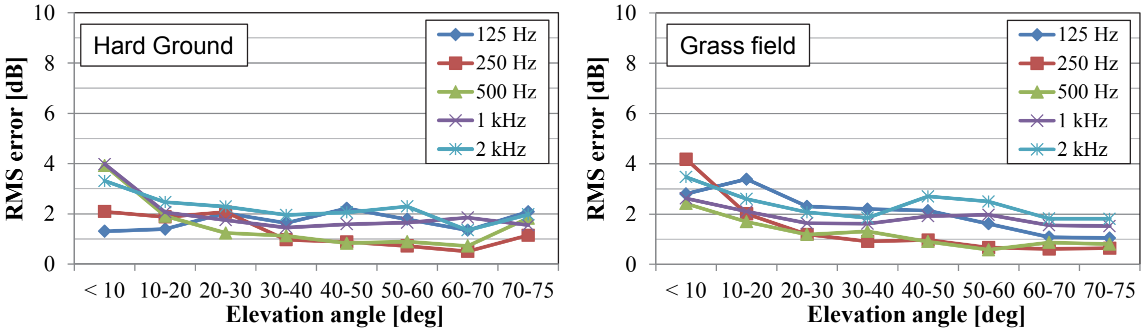
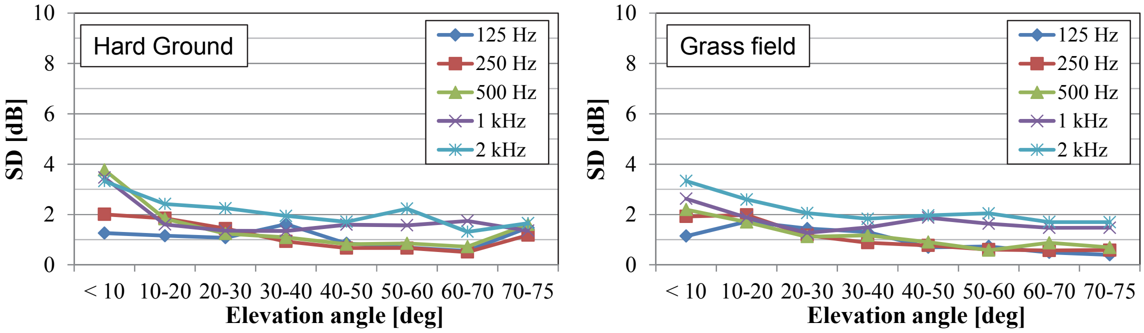


Figure 5 – Comparisons between experiments and calculations
(Source Height: 100 m, Ground condition: Hard)

In order to evaluate the calculation accuracy, arithmetic average of five values of excess attenuation in each trial obtained by the measurements and the calculations has been calculated, and their level difference has been evaluated as the prediction error for the trial. Figure 6 shows the root-mean-square value (RMS) and standard deviation (SD) of the prediction error obtained in all trials. The data of the trials in which impulse response measurements conducted less than 5 times have been excluded from the calculation of RMS and SD. It is seen that the RMS and SD are within 3 dB in almost all conditions. It is also found, however, that RMS and SD in low elevation angle conditions below 10 degrees become slightly large compared with those in other conditions and exceed 3 dB. In order to realize further improvement of the prediction accuracy on sound propagation from such low elevation angles, it might be necessary to set the parameters more precisely in the GF-PE calculations on meteorological conditions near ground including the parameters on atmospheric turbulence and/or on the ground impedance



(a) RMS of level differences



(b) SD of level differences

Figure 6 – RMS and SD of level differences between measurements and calculations

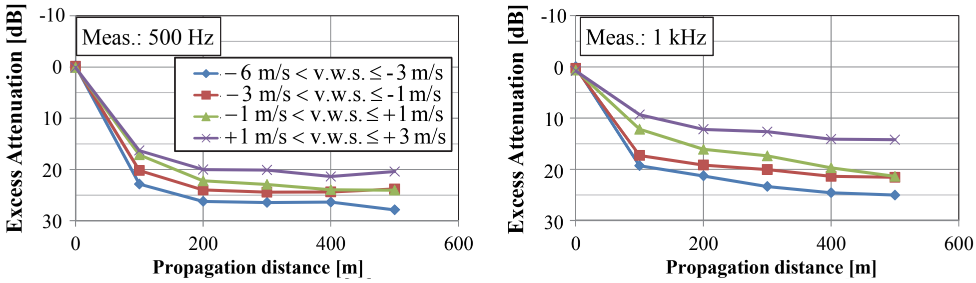
3.4 Study on the Modification of Prediction Accuracy

In the previous section, the prediction error in the condition of sound propagation from low elevation angle below 10 degrees becomes large compared with that in the conditions from higher elevation angle. So, we have tried to modify the effective sound speed profiles near ground assumed in the GF-PE calculations, and confirmed the applicability of the modification by comparing the calculation results with the measurements in cases of GtoG sound propagation over grass field. In the modification, the profiles of wind speed and temperature have been assumed according to the Monin-Obukhov similarity theory (4,5,6). The vertical fluxes on momentum F_M and heat F_H for 1-minute were obtained from measured data of the 3 dimensional ultrasonic anemometer (sampling frequency at 4 Hz) set in the experiment field as shown in Fig. 1.

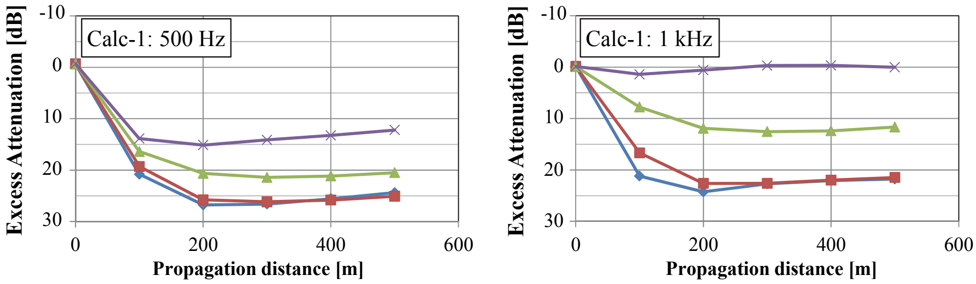
Figure 7 shows the comparisons of excess attenuation in Exp-2 among measurements, previously described calculations (Calc-1) and calculations assuming the modified effective sound speed profiles (Calc-2). In Calc-1, variation in excess attenuation due to meteorological effects becomes larger than that obtained by measurements. On the other hand, the range of the variation in excess attenuation obtained by Calc-2 approaches to that of the measurements. In the Exp-2, many of the measurements were carried out in unstable atmosphere conditions as shown in Table 2. It is considered that the gradient of vertical profiles of wind speed assumed in the Calc-1 might be larger than that of actual conditions because the profiles were assumed regardless of atmospheric stability conditions. On the other hand, the gradient of vertical profiles of wind speed assumed in Calc-2 might become closer to the actual conditions by assuming the profiles according to the Monin-Obukhov similarity theory.

4. CONCLUSIONS

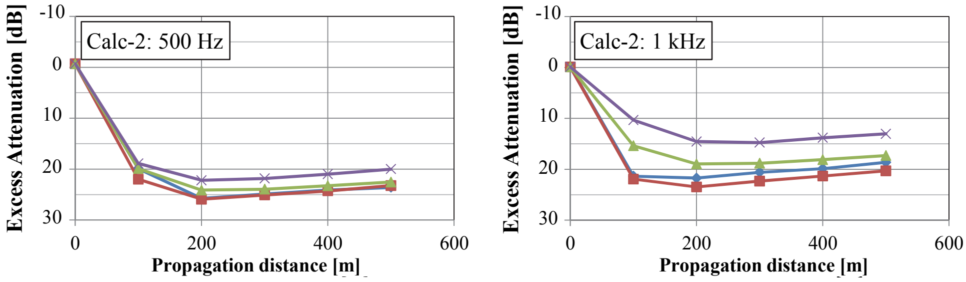
Meteorological and ground effects on Air-to-Ground outdoor sound propagation have been investigated by conducting two series of impulse response measurements with the aid of a loudspeaker suspended by a tethered balloon. As a result, it has been found that the difference in excess attenuation due to the difference in ground property is occurred in cases that sound propagation from a sound source in elevation angle below 30 degrees. It meets the condition that the Fresnel number is below 1 when the height of the receiving point is about 1.2 m. In the experiments, measurements of Air-to-Ground sound propagation and Ground-to-Ground sound propagation were conducted repeatedly with a short time interval. It has been clearly confirmed that the meteorological effects on Air-to-Ground sound propagation are small compared with that on Ground-to-Ground sound propagation under the same meteorological conditions. It has been also found that it is difficult to discuss the variation in Air-to-Ground sound propagation only by the vector wind speed near ground. By comparing the measurements and calculations using the GF-PE method which takes into account of atmospheric turbulent effect, it has been verified that our propagation model based on the GF-PE method under development has good applicability to the prediction of Air-to-Ground sound propagation. In addition, it has been also found that the applicability of the model in the conditions of sound propagation from low elevation angle might increase by assuming the sound speed profiles according to the Monin-Obukhov similarity theory using the data observed by a 3 dimensional ultrasonic anemometer.



(a) Measurements



(b) Prior calculations



(c) Modified calculations

Figure 7 – Comparisons of EA between measurements and two kinds of calculations

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