Ultrasonic Doppler Speed Sensor for Agricultural Vehicles: Effects of Pitch Angle and Measurements of Velocity Vector Components

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ABSTRACT

High-precision ground speed sensors could be used as a component of navigation or control systems for agricultural vehicles. This paper describes the characteristics of the speed sensor developed by the authors, focusing on the effects of pitch angle. For this purpose, experiments were carried out at various sensor depression angles. The results showed that the output was almost the same as the theoretical value for depression angles of 40 to 50 degrees, although the measurement error was relatively large in the case of artificial turf with short pile. Measurement tests at various angles between the traveling direction and the sensor direction in the horizontal plane were also carried out to determine the possibility of velocity vector measurement including sideslip. It was estimated that the measurement error would be within 3% of the absolute velocity in any direction. The results suggested that it is possible to measure the velocity vector without the effects of pitch angle by using multiple sensors facing in different directions.

Keywords: Ultrasonic, Doppler, speed sensor, agricultural vehicles, pitch angle, sideslip, Japan

1. INTRODUCTION

Accurate speed measurement of agricultural vehicles has become important recently. It will improve the autonomous control systems for agricultural vehicles (Ishida et al., 1998) and (Imou et al., 1998), and will also be useful for the monitoring of control systems of sophisticated vehicles used in precision agriculture. Alternatively, RTK-GPS receivers could be used for these purposes (Noguchi et al., 2002), but they are still very expensive, require a base station near the area of operation, and they cannot be used in the area where the RF signals cannot be received (Zeitzew, 2007).

Ground speed has been measured with a fifth wheel, however, it might slip on soft surfaces. Tompkins et al. (1988) evaluated the performances of fifth wheel, front wheel and microwave Doppler speed sensors on various surfaces, and concluded that the microwave sensor tented to produce a more accurate indication than other sensors. These evaluation tests were performed at speeds of 4, 7, and 10 km/h. But, the slower speed needs to be measured for the application for navigation systems.

Microwave and ultrasonic Doppler speed sensors are now commercially available. However, conventional sensors were originally intended for monitoring tractor performance; most of them are not good for detecting motions at lower speeds, and some of them cannot determine reverse motion. Hata et al. (1991) investigated commercial microwave Doppler speed sensors under various working conditions. And based on those results, they developed an ultrasonic Doppler speed sensor. It could measure in a relatively low speed range from the lowest of 0.1 m/s. Ultrasonic speed sensors have been studied also for measuring speed of automobiles (Kobayashi et al., 1990, 1991; Nakamura et al., 1990). Most of those studies aimed to measure higher speeds.

With this back ground, we developed an ultrasonic Doppler speed sensor using a new signal processing method. The sensor could measure the speeds of both forward and reverse motion, including very low speed motion, with relatively high accuracy compared to the conventional sensors. The results of indoor tests on the developed sensor were reported in (Imou et al., 2001a). The sensor was improved in a later study to increase the sensitivity, and the results of indoor and field tests were reported in (Imou et al., 2001b). Another type of sensor was also developed using a parabolic reflector, as described in (Imou et al., 2001c).

In our previous study, the speed sensors were tested in a fixed attitude to determine the basic characteristics. Most of other previous studies were also performed in a fixed attitude, and so the effects of the change in attitude have not been reported to our knowledge. However, in the case of agricultural vehicles, the depression angle of the sensor might change as the vehicle attitude changes in actual field operations, which may affect the measurement results. In this study, we investigated the effects of pitch angle variations. However, although the pitching motion might affect the measurements, dynamic tests were not conducted at this stage. Rather, the measurement tests were carried out at various depression angles, but in a given trial the angle was kept constant during the motion to determine its effect.

Speed measurement tests including lateral motion were also conducted, which simulated sideslip of the vehicle. The traveling direction of the vehicle changes due to sideslip, and so the direction of motion does not always correspond to the sensor direction. Therefore, the experiments were conducted at various angles between the sensor and traveling directions. We showed that the velocity vector including sideslip can be measured accurately using two sensors facing in different directions.

These experiments were conducted in a laboratory using test measurement equipment to evaluate the sensor under constant, reproducible conditions.

2. EQUIPMENT AND METHODS

2.1 Speed Sensor

The same type of speed sensor was used in this study as in the previous studies, and the principle and basic construction of the sensor have already been reported in (Imou et al., 2001a) and (Imou et al., 2001b). Therefore, a detailed description of the sensor is omitted here, and only the setting of the output frequency is described because it is directly related to the contents of this report. The speed sensor transmits an ultrasonic beam onto the ground surface in an inclined direction, and it detects the Doppler shift of the reflected sound wave. Assuming that air is stationary relative to the ground, the frequency of the received wave is given by:

$$F_R = F_0 \frac{C_S + V\cos\alpha}{C_S - V\cos\alpha} \approx F_0\left(1 + \frac{2V}{C_S}\cos\alpha\right) \qquad (1)$$

where,
F_0: frequency of the transmitted wave

F_R: frequency of the received wave
C_S: sound velocity
V: vehicle velocity relative to the ground
α: angle between the vehicle velocity vector and the transmitted ultrasonic beam

Conventional Doppler speed sensors mix the signals of the transmitted and received waves and output the beat of the two signals, in which the output frequency is equal to the absolute value of the Doppler shift. Therefore, they cannot distinguish between forward and reverse motion. In this case, accurate velocity measurement is difficult when the vehicle stops or travels at a very low speed because the Doppler shift approaches zero while the phase of the received signal varies due to vibrations caused by the engine or the wind.

We solved this problem in the developed sensor, in which the frequencies of the transmitted and received signals are multiplied by slightly different factors by using a frequency synthesizer and a frequency multiplier, and the signals are mixed. In this case, the output frequency is given by:

$$F_{OUT} = K_R F_R - K_0 F_0 \approx (K_R - K_0) F_0 + K_R F_0 \frac{2V\cos\alpha}{C_S} \qquad (2)$$

where,
F_{OUT}: output frequency of the sensor
K_0: multiplying factor for the transmitted signal
K_R: multiplying factor for the received signal

The sensor used in the experiments transmits an ultrasonic wave of 200 kHz, and the multiplying factors were set as $K_0 = 4.75$ and $K_R = 5$. The sensor was mounted at 45 degrees downward from the horizontal. Assuming that the depression angle is equal to α and the sound velocity C_S is 340 m/s, Equation (2) can be rewritten as:

$$F_{OUT} \approx 50 + \frac{1000\sqrt{2}}{340} V \qquad (3)$$

This equation indicates that the output frequency is 50 kHz when the vehicle stops and the rate of change in output frequency is proportional to the traveling speed, and is calculated to be about 4.2 kHz for the speed of 1 m/s. The value changes with the temperature because of the temperature dependence of the sound velocity. The temperature rise of 1 degree Celsius would decrease the value by about 0.18 %. The effect of humidity might be almost negligible. When the temperature is 15 degree Celsius, 10 % increase of the relative humidity would increase the value by only about 0.03 %. Effects of the wind on ultrasonic Doppler speed measurement were tested by Hata et al. (1991). They reported that the measurement error of a maximum of 2 % would be caused by wind in practical operating conditions.

Figure 1 shows the speed sensor, which was improved based on the previous studies. In particular, the vibration isolation has been improved both mechanically and electronically to avoid the transmitted signal affecting the received signal when the received wave is weak.

2.2 Test Equipment

The experiments were conducted using the test measurement equipment shown in Figure 2, which was the same as that used in the previous studies. The sensor was mounted on a linear actuator (THK, Model LV200+4000L) and moved horizontally above the model ground surface. The actuator has a distance of motion of 4 m, maximum speed of 2 m/s and maximum acceleration of 4 m/s^2. The model ground surfaces used for the tests were as outlined below, as shown in Figure 3.

(a) Artificial turf (long) with 22-mm long pile (trade name "Astroturf")
(b) Artificial turf (short) with curled 10-mm long pile designed for baseball fields
(c) Wooden semicolumns glued on plywood

2.3 Test Methods

The experiments were designed to investigate the effects of the pitch angle on the speed measurement and to examine the possibility of determining the velocity vector including sideslip. For the first set of experiments, the depression angle θ, which is indicated in Figure 4(a), was changed from 30 to 60 degrees in 5-degree steps as a parameter. With horizontal motion over a flat surface, the angle θ approximately corresponds to the angle α in Equations

Fig. 1. Ultrasonic Doppler speed sensor

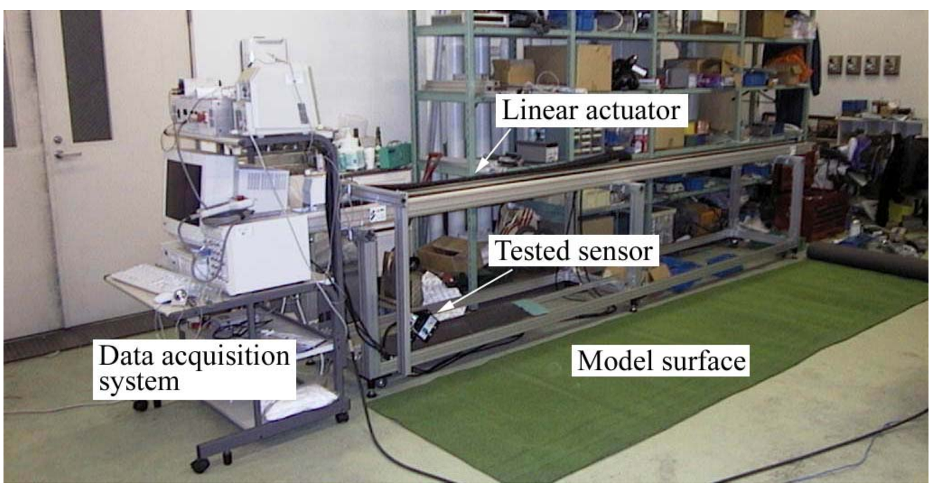
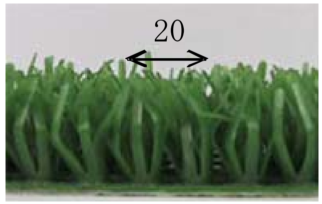
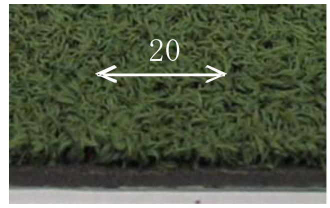


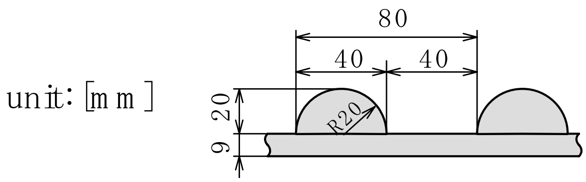
Fig. 2. Test equipment for Doppler speed sensor



(a) Artificial turf (long)



(b) Artificial turf (short)



(c) Wooden semicolumns

Fig. 3. Model ground surfaces

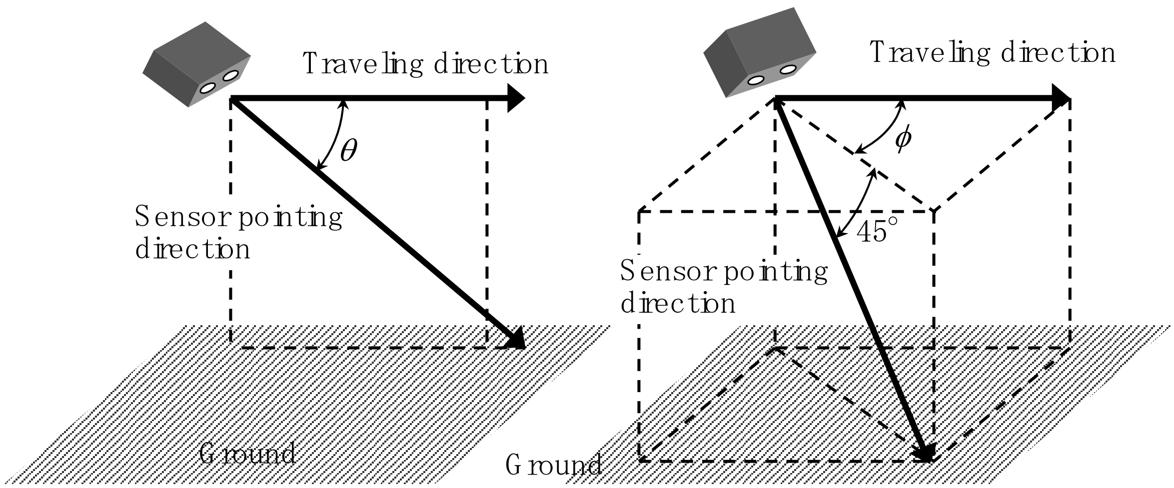


Fig. 4. Sensor pointing directions as parameters in the experiments

(1) and (2) because the sonic beam is narrow. The change in roll angle has little effect on the one directional speed measurement (Imou et al., 2001c). Even if the direction of the sonic beam was shifted in the lateral direction due to the rolling, the reflection angle of the beam on the ground would be almost constant. Therefore, the change in roll angle was not tested in this study.

For the second set of experiments, whose purpose was to measure the velocity vector components, we mounted the sensor on the actuator in the direction as shown in Figure 4 (b). Letter ϕ indicates the angle between the traveling direction and the sensor direction in the horizontal plane. This azimuth angle was changed in the tests from 0 to 90 degrees in 15-degree steps as a parameter. The depression angle was fixed at 45 degrees in this case. We used only the artificial turf ground surfaces for these tests because the wooden semicolumns were attached laterally and therefore could not reflect the sound wave back to the sensor, except in the case when the angle ϕ was zero.

The sensor was set at 45 cm above the ground surface in both tests, and the test measurements were conducted at seven speed settings in both forward and reverse motions: 0.01, 0.05, 0.1, 0.5, 1, 1.5 and 2 (m/s).

3. RESULTS AND DISCUSSION

3.1 Effects of Depression Angle

Examples of the experimental results are shown in Figure 5, which were obtained in the tests on the artificial turf (long). The ambient air temperature was 22°C during the tests. The plots show the average values of output frequency in uniform motion. The lines are the regression lines of the plots for every θ value. The small graph in the upper left is an enlarged view of the plots in the vicinity of zero speed. The intercepts of the regression lines were fixed to 50 kHz in the linear regression because the output frequency at zero speed was set at 50 kHz. Gradients of the regression lines and the coefficients of determination R^2 for all surfaces are shown in Table 1. The results for the artificial turf (long) showed that the change in output frequency was almost proportional to the speed at every θ value. The correlation coefficients were quite high, between 0.9977 and 1.0000. The sensor showed good linearity and it could measure speeds of as low as 10 mm/s at any depression angle. In the case of the artificial turf (short), the correlation coefficients were between 0.9592 and 1.0000. The results for the wooden semicolumns showed better linearity, in which the correlation coefficients were 0.9999 or 1.0000.

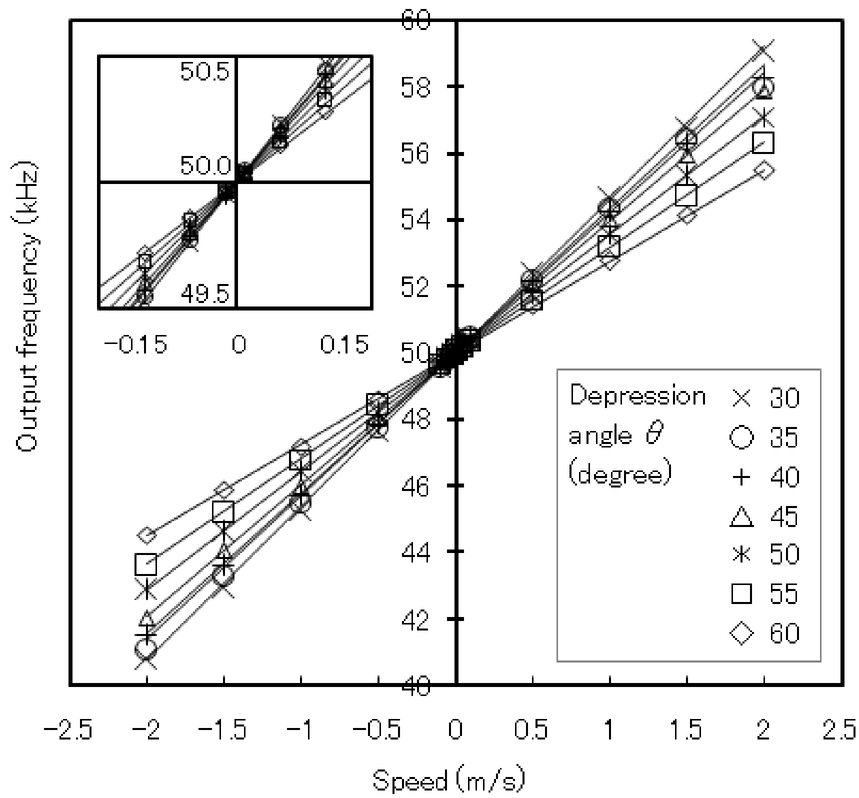


Fig. 5. Output frequency as a function of traveling speed with a parameter of the depression angle on the artificial turf with long pile

Tables 2, 3 and 4 show the standard error of dynamic measurement, which is the standard deviation of the measured values from the regressed value that was obtained from the regression equation shown in Table 1. Each value of the error is expressed in the unit of cm/s. The data was obtained from the values measured every 100 ms during the constant motions in the tests. The lower the speed, the higher the ratio of the displacement to the speed became. The main factor of the errors is considered to be the time variations of the measured values. The measured values on the artificial turf (short) at the depression angles of 30 and 35 degrees were unstable, and thus the standard errors became large.

Table 1. Regression coefficients of the mean output at different depression angles

Depression angle θ (degree)	Artificial turf (long)		Artificial turf (short)		Wooden semicolumns	
	Gradient*	R^2**	Gradient*	R^2**	Gradient*	R^2**
30	4.649	0.9996	4.146	0.9899	4.867	1.0000
35	4.356	0.9977	3.649	0.9592	4.620	0.9999
40	4.254	0.9998	4.032	0.9962	4.378	1.0000
45	4.006	1.0000	3.894	1.0000	4.094	1.0000
50	3.602	1.0000	3.510	0.9994	3.668	1.0000
55	3.205	0.9999	3.111	0.9997	3.260	0.9999
60	2.782	0.9999	2.755	0.9997	2.864	1.0000

* Gradient of the regression line in the unit of [kHz/(m/s)]
** Correlation coefficient

Table 2. Standard error of dynamic measurement from the regressed value at different depression angles on the artificial turf (long)

Speed (m/s)	Standard error (cm/s) Depression angle θ (degree)						
	30	35	40	45	50	55	60
2.00	4.52	15.23	6.19	3.40	3.82	5.08	3.94
1.50	6.86	6.59	2.44	2.71	2.56	3.54	3.46
1.00	3.40	4.80	2.20	1.71	1.68	2.47	3.84
0.50	2.10	2.53	1.64	1.50	1.47	1.80	2.13
0.10	0.93	0.96	0.66	0.55	0.80	0.84	0.93
0.05	0.63	0.85	0.84	0.37	0.49	0.58	0.62
0.01	0.21	0.17	0.12	0.15	0.14	0.21	0.22
-0.01	0.18	0.28	0.13	0.13	0.15	0.18	0.20
-0.05	0.57	0.54	0.45	0.36	0.60	0.56	0.51
-0.10	0.59	0.77	0.53	0.55	0.65	0.77	0.92
-0.50	2.29	2.81	1.51	1.14	1.59	1.56	2.34
-1.00	3.97	4.93	2.62	1.99	2.05	2.83	4.04
-1.50	4.64	6.98	2.45	2.03	2.73	3.57	3.11
-2.00	3.38	7.64	5.80	3.44	1.92	3.62	5.82

Table 3. Standard error of dynamic measurement from the regressed value at different depression angles on the artificial turf (short)

Speed (m/s)	Standard error (cm/s) Depression angle θ (degree)						
	30	35	40	45	50	55	60
2.00	27.18	58.14	17.31	3.95	8.47	5.66	7.28
1.50	15.33	19.86	7.87	4.57	4.00	4.09	2.65
1.00	6.36	10.51	4.67	2.58	3.91	3.13	2.93
0.50	6.02	6.97	2.95	1.51	2.22	2.07	2.00
0.10	1.93	2.31	1.54	0.67	1.15	1.17	0.99
0.05	1.25	1.97	1.10	0.51	0.60	0.82	0.64
0.01	0.24	0.31	0.20	0.17	0.18	0.20	0.23
-0.01	0.17	0.42	0.19	0.16	0.16	0.19	0.20
-0.05	1.05	1.47	0.90	0.39	0.49	0.66	0.77
-0.10	1.67	2.45	1.52	0.62	0.81	1.00	0.92
-0.50	7.47	11.20	3.91	1.64	2.08	2.54	1.87
-1.00	13.98	21.29	7.70	2.43	4.15	3.70	3.43
-1.50	15.93	30.48	9.56	3.73	4.98	3.84	4.08
-2.00	14.20	35.57	10.81	3.03	5.11	5.44	3.68

Table 4. Standard error of dynamic measurement from the regressed value at different depression angles on the wooden semicolumns

Speed (m/s)	Standard error (cm/s) Depression angle θ (degree)						
	30	35	40	45	50	55	60
2.00	2.59	4.50	2.59	1.34	2.05	2.36	6.53
1.50	2.20	2.32	1.85	1.42	2.00	7.74	5.42
1.00	1.35	2.02	1.39	1.42	1.32	1.87	3.72
0.50	0.81	1.20	1.08	1.05	1.14	1.22	2.51
0.10	0.70	0.64	0.43	0.45	0.55	0.69	0.84
0.05	0.28	0.45	0.31	0.34	0.42	0.51	0.62
0.01	0.11	0.31	0.20	0.13	0.12	0.17	0.25
-0.01	0.09	0.37	0.12	0.13	0.12	0.18	0.23
-0.05	0.28	0.37	0.32	0.32	0.42	0.47	0.51
-0.10	0.36	0.44	0.40	0.45	0.54	0.61	0.88
-0.50	0.72	0.89	1.01	0.93	1.22	1.39	2.38
-1.00	1.23	1.93	1.77	1.29	1.19	1.64	4.13
-1.50	1.27	2.06	1.64	1.90	2.02	2.85	4.60
-2.00	2.14	1.43	4.05	1.87	3.81	3.71	7.33

The relation between the speed and the average output frequency was found to be linear at every depression angle and for every ground surface. Therefore, we evaluated the effects of the depression angle by the ratio of change in output frequency to the change in speed (i.e. the gradient of the regression line). As shown in Figure 5, the larger the depression angle, the smaller the change in output frequency. This is explained by Equation (1). A larger angle α makes the Doppler shift smaller. The rate of change in output frequency on every ground

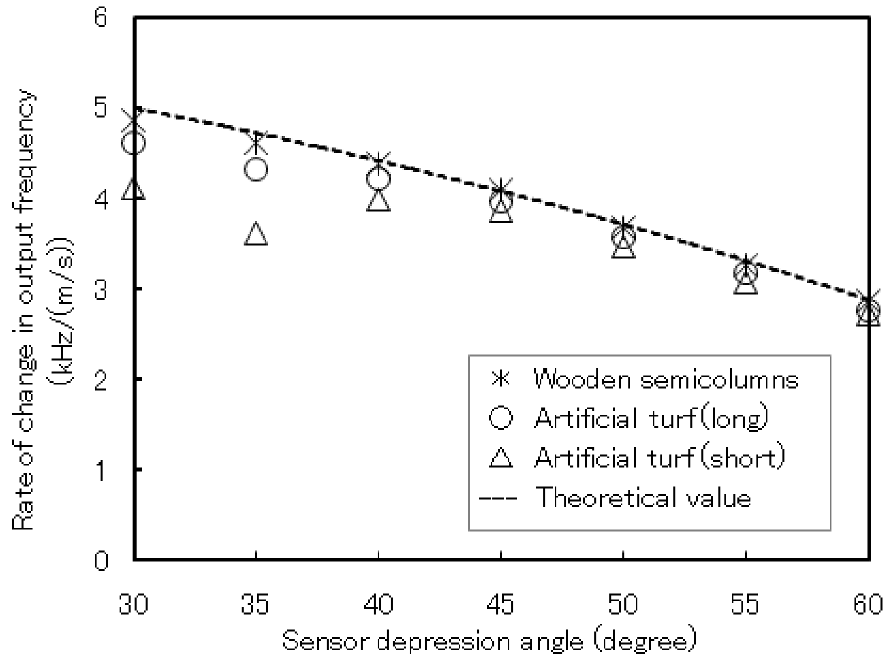


Fig. 6. Rate of change in output frequency per unit change in speed as a function of the sensor depression angle

surface is shown in Figure 6. The broken line indicates the theoretical value. The output frequency slightly varied according to the surface (Tompkins et al., 1988). The results for the wooden semicolumns were close to the theoretical curve. A semicolumn is considered to be able to reflect sound waves in all directions. In the case of the artificial turf (long), the results were almost the same as the theoretical values when the depression angle was larger than 40 degrees, but the differences were considerable at smaller depression angles. The results for the artificial turf (short) were more different from the theoretical values, especially at depression angles of less than 40 degrees. Because the artificial turf (short) has a smoother surface than the others, most of the sound wave is reflected forward when the depression angle is small, and so the sensor cannot receive sufficiently strong signals, resulting in larger errors.

The error of the speed measurement was estimated from the data shown in Figure 6. If the calibration test is conducted at a fixed depression angle and the obtained calibration coefficient is used to determine the speed from the output frequency, an error may occur when the depression angle changes with the pitch angle. Figure 7 shows the estimated error. The broken line indicates the theoretically predicted error and the plots show the errors estimated from the experimental results. In this case, the calibration test is assumed to be conducted on each different types of ground surface with the depression angle of 45 degrees. Therefore, all plots of 45 degrees correspond to zero. We found in our previous study that the pitch angle of a tractor changes between about –5 and +5 degrees on a flat forage production field (Imou et al., 1997). In this case, the change in pitch angle may cause a measurement error of about 10%, which may not be negligible.

The error due to fluctuations in pitch can be reduced by using an additional sensor. If two sensors are mounted facing forward and backward and the average output of the two sensors is

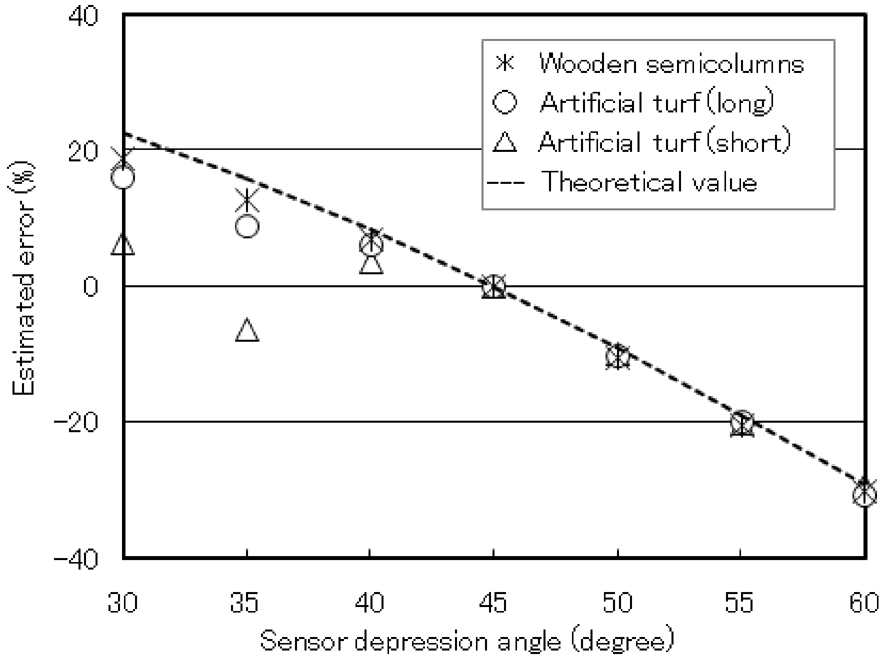


Fig. 7. Estimated error of the speed measurement caused by the change in sensor depression angle

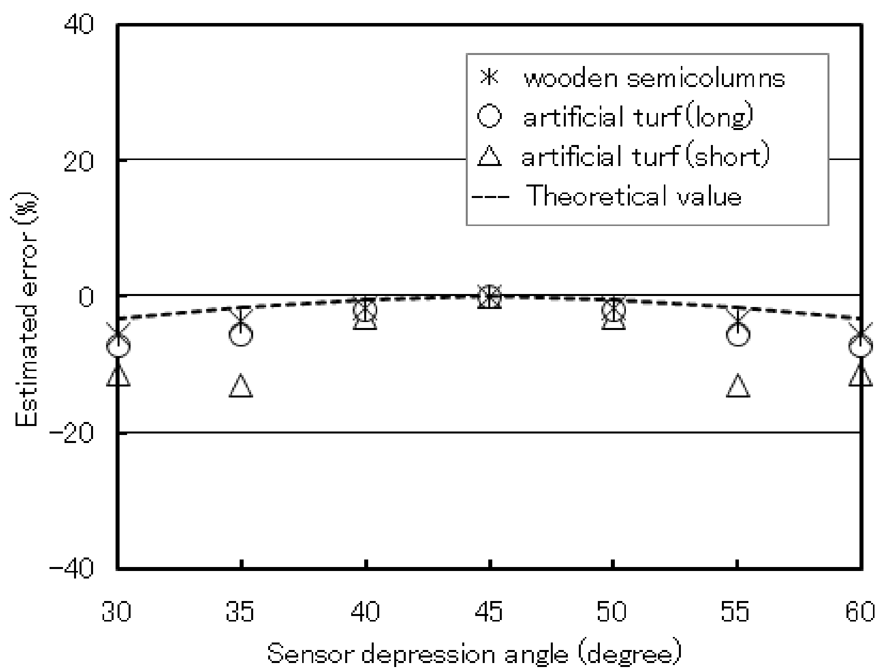


Fig. 8. Estimated error of the speed measurement caused by the change in sensor depression angle when one more sensor is used facing the opposite direction

used to determine the speed, the pitch-related errors may cancel each other, because the change in pitch angle makes the depression angle of one sensor larger and that of the other smaller. Figure 8 shows the estimated error in this case. It is assumed that both sensors are set at the depression angle of 45 degrees. The meanings of the broken line and the plots are the same as those in Figure 7. It is shown that the error can be significantly reduced at depression angles of between 40 and 50 degrees. The error is larger for the artificial turf (short) compared to the other surfaces, but is estimated to be less than 3% in this range of depression angle. The instantaneous error is estimated to be the sum of this average value and the dynamic fluctuation shown Tables 2, 3 and 4.

3.2 Measurements of Velocity Vector Components

Figure 9 shows examples of the results obtained on the artificial turf (long). The ambient air temperature was 15°C. The plots show the average values of output frequency in uniform motion. The lines are the regression lines of the plots for every ϕ value. The intercepts of the regression lines were fixed to 50 kHz as in the previous section. Gradients of the regression lines and the coefficients of determination R^2 for the two tested surfaces are shown in Table 5. The larger the angle ϕ, the smaller the gradient of the regression line. This is because the component of the velocity vector in the sensor pointing direction becomes smaller as the angle ϕ becomes larger. When the angle ϕ is 90 degrees, the sensor moves orthogonal to the boresight direction and so the output frequency should be 50 kHz, as in the case when the sensor does not move. In the experiments, the outputs were approximately 50 kHz when the sensor was stationary, with small differences in frequency when ϕ was 90 degrees.

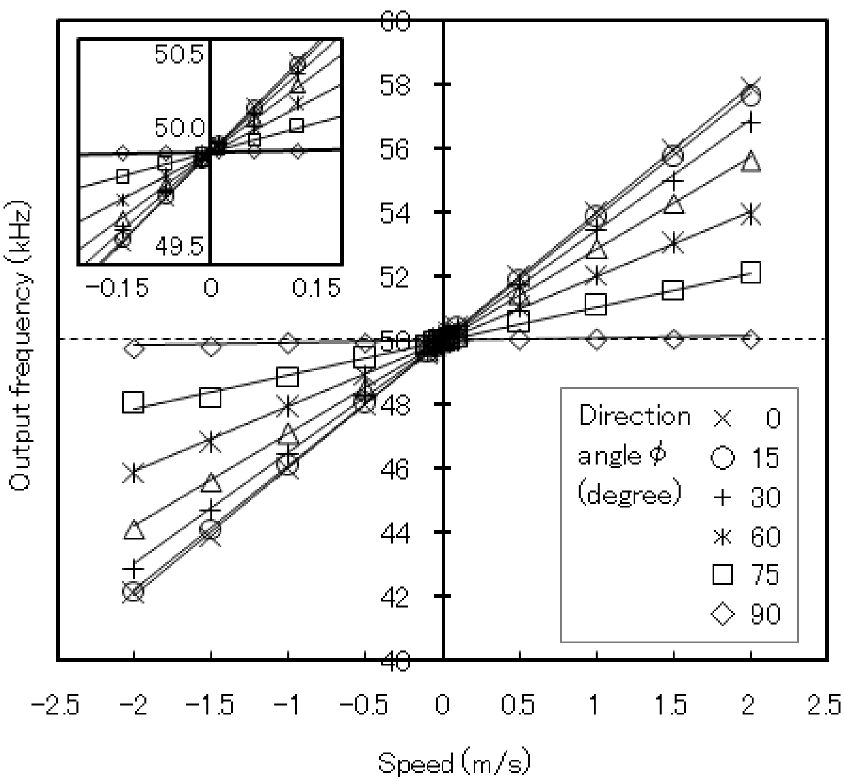


Fig. 9. Output frequency as a function of traveling speed with a parameter of the traveling direction on the artificial turf with long pile

The results for the artificial turf (long) showed good linearity for every ϕ value. The correlation coefficients were between 0.9969 and 0.9999 except in the case in which ϕ was 90 degrees. When ϕ was 90 degrees, all plots were close to the same value and even small deviations might reduce the correlation coefficients. The correlation coefficient was 0.826 in this case. Similar results were shown for the artificial turf (short): the correlation coefficient was 0.9498 when ϕ was 90 degrees, and was between 0.9992 and 0.9998 for other values of ϕ.

These regression coefficients were obtained from the average values of output frequency. The instantaneous error is induced also from dynamic fluctuation. Tables 6 and 7 show the standard error of dynamic measurement from the regression equation. The data was obtained from the values measured every 100 ms during the constant motions.

Table 5. Regression coefficients of the mean output at different directions

Direction angle ϕ (degree)	Artificial turf (long)		Artificial turf (short)	
	Gradient*	R^2**	Gradient*	R^2**
0	3.945	0.9999	3.844	0.9989
15	3.834	0.9999	3.774	0.9998
30	3.433	0.9994	3.422	0.9998
45	2.863	0.9997	2.794	0.9998
60	2.015	0.9992	2.011	0.9995
75	1.052	0.9969	1.071	0.9992
90	0.074	0.8291	0.101	0.9498

* Gradient of the regression line in the unit of [kHz/(m/s)]
** Correlation coefficient

Table 6. Standard error of dynamic measurement from the regressed value at different directions on the artificial turf (long)

Standard error (cm/s)							
Speed (m/s)	Direction angle ϕ (degree)						
	0	15	30	45	60	75	90
2.00	5.74	5.53	4.43	3.97	3.26	3.11	1.84
1.50	3.83	3.29	3.36	3.83	2.12	2.38	2.51
1.00	3.70	2.37	2.92	2.10	2.25	1.96	2.22
0.50	1.94	1.99	1.89	1.60	1.59	1.59	1.49
0.10	0.81	0.81	0.89	0.77	0.73	0.69	0.69
0.05	0.58	0.58	0.60	0.51	0.52	0.49	0.47
0.01	0.21	0.29	0.28	0.23	0.22	0.21	0.26
-0.01	0.22	0.25	0.27	0.23	0.21	0.20	0.19
-0.05	0.58	0.55	0.56	0.52	0.52	0.47	0.48
-0.10	0.85	0.81	0.80	0.75	0.75	0.70	0.65
-0.50	1.81	1.69	1.76	1.77	1.72	1.52	1.64
-1.00	2.92	2.57	2.53	1.96	2.59	2.07	1.82
-1.50	4.05	3.18	3.71	3.41	2.69	3.22	3.21
-2.00	6.10	2.80	3.88	3.79	4.53	3.56	3.16

Table 7. Standard error of dynamic measurement from the regressed value
at different directions on the artificial turf (short)

Standard error (cm/s)							
Speed (m/s)	Direction angle ϕ (degree)						
	0	15	30	45	60	75	90
2.00	4.09	4.58	6.69	5.02	5.27	3.39	3.18
1.50	4.63	3.57	2.33	3.24	2.56	2.71	2.63
1.00	2.22	2.31	2.01	2.53	2.16	2.17	2.07
0.50	1.66	1.63	1.43	1.69	1.64	1.72	1.53
0.10	0.67	0.66	0.75	0.70	0.74	0.70	0.70
0.05	0.46	0.47	0.49	0.50	0.50	0.49	0.48
0.01	0.17	0.19	0.19	0.24	0.20	0.19	0.23
-0.01	0.19	0.20	0.22	0.24	0.21	0.19	0.22
-0.05	0.46	0.44	0.49	0.50	0.48	0.49	0.50
-0.10	0.60	0.62	0.71	0.73	0.72	0.74	0.71
-0.50	1.55	1.65	1.80	1.85	1.82	1.72	1.44
-1.00	2.58	2.00	2.26	2.97	2.57	2.41	1.58
-1.50	5.42	2.59	3.52	3.42	3.11	2.57	2.08
-2.00	3.23	3.00	4.09	3.20	2.98	3.53	2.53

We evaluated the effects of the angle ϕ by the ratio of change in output frequency to the change in speed as in the previous section. Figure 10 shows the relation between the change in output frequency (i.e., the gradient of regression line) and the angle ϕ on the artificial turfs. The broken line indicates the theoretical value. The ratio of change in the output was a little less than the theoretical value, but the effects of the angle ϕ showed almost the same tendency as the theory. The difference was due to the fact that the sound beam had a certain width and so the sensor pointing direction did not exactly coincide with the direction of the sound wave returning to the sensor from the ground (Imou et al., 2001c). To compensate for these differences, calibration must be conducted on the same type of ground where the vehicle is used.

Here, we assume that the calibration is conducted for each different types of ground surface with the angle ϕ set at 0 degree and the speed is determined from the output frequency by multiplying the calibration coefficient. In this case, the estimated errors in the measurements of the vector components are shown in Figure 11. When the vehicle moves at the speed of V, the vector component in the ϕ direction is $V\cos\phi$, but the error ε will be included in the measurement. The horizontal axis of Figure 11 is the angle ϕ and the vertical axis is the error ratio given by ε/V. The values of the error were calculated for each artificial turf from the experimental results shown in Figure 10, and were estimated to be positive and less than 3% in any direction. Of course, errors may be induced for other reasons such as the fluctuation shown in Tables 6 and 7. However, the error caused by the effects of angle ϕ is considered to be in an acceptable range, and thus these results suggest that the velocity vector can be measured using multiple sensors facing in different directions.

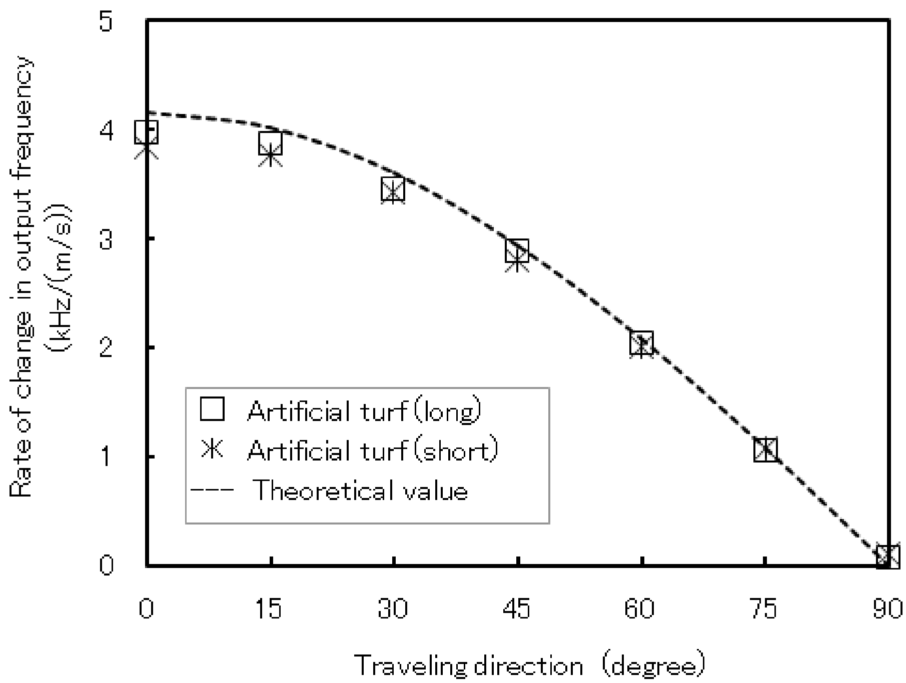


Fig. 10. Rate of change in output frequency per unit change in speed as a function of the traveling direction

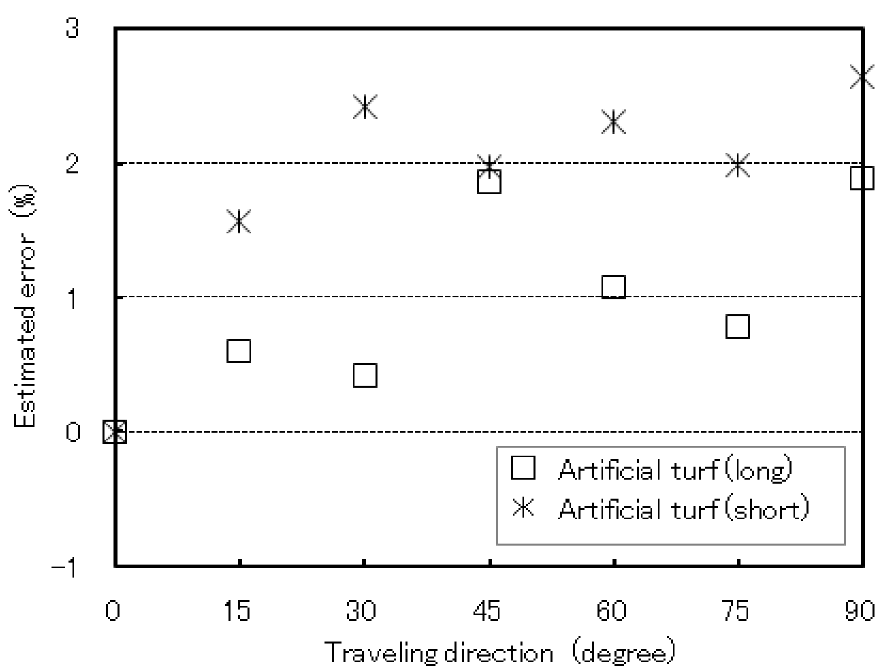


Fig. 11. Estimated error in the measurement of the velocity vector component

4. SUMMARY AND CONCLUSIONS

Effects of the pitch angle and the traveling direction were investigated for the newly developed ultrasonic Doppler speed sensor. Experiments were carried out for various depression angles of the sensor, and for various angles between the traveling direction and the sensor direction. The results may be summarized as follows:

1) The relation between the speed and the average output frequency was linear at every depression angle and for every ground surface. The ratio of the change in output to the speed was close to the theoretical value at every depression angle for the surface of wooden semicolumns. For the artificial turf with long pile, the ratio was almost the same as the theoretical value at angles of larger than 40 degrees. However, it was considerably different from the theoretical value at smaller angles. The results for the artificial turf with short pile were more different from the theoretical values especially at angles of less than 40 degrees, which was due to its smoother surface than the others. For every surface, it was estimated that the error induced by the change in pitch angle can be reduced to less than 3% in the range of pitch angle between –5 and +5 degrees using two sensors, one facing forward and the other facing backward.

2) The relation between the speed and the average output frequency was linear at every angle between the traveling and the sensor directions in the horizontal plane. Average value of the components of velocity vector could be measured in any direction with an error of less than 3% of the absolute speed for both artificial turf types. The instantaneous error is estimated to be the sum of this error of average value and the dynamic fluctuation.

3) These results suggest that the effects of the pitch angle will be cancelled and the velocity vector can be measured using multiple sensors pointing in multiple directions.

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