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Fig. 1. The time dilation of ultrasonic single-bit signal.

![Diagram](image1)

Fig. 2. Time dilation correlation result.

![Diagram](image2)

Fig. 3. Situations where the Doppler effect may occur. S and R represent the sound source and receiver, respectively.

III. DOPPLER EFFECT

The situation studied in this paper differs from the general case of the Doppler effect. Fig. 3 (a) shows the situation for a commonly known Doppler effect. The source generating the ultrasound wave is labeled S and the sound receiver is labeled R. The source and receiver are separated from each other and have speeds of $V_s$ and $V_r$, respectively. The situation that arises in this study is Fig. 3 (b). The source and receiver are identical and analyze the echo. The speeds of the sensor user and the target are $V$ and $V_t$, respectively. Because of this difference, the frequency and wavelength of the received sound waves are expressed differently in the two situations. Equation (4) is for a general situation of Fig. 3 (a), and the measurement conditions in this study are shown in Fig. 3 (b), and (5) is applied.

$$f_r = \frac{C - V_r}{C - V_s} f$$

$$T_r = \frac{C - V_s}{C - V_r} T_s$$

where $f$ and $T$ are frequency and wavelength of transmitted sound, $f_r$ and $T_r$ are frequency and wavelength of received sound and $C$ is the speed of sound.

$$f' = \frac{(C + V)(C - V_i)}{(C - V)(C + V_i)} f$$

$$T' = \frac{(C - V)(C + V_i)}{(C + V)(C - V_i)} T$$

where $f$ and $T$ are frequency and wavelength of transmitted sound as in (4), $f'$ and $T'$ are frequency and wavelength of received sound.

Equation (1) and (5) can be summarized as follows.

$$\gamma = T' T \frac{(C + V)(C - V_i)}{(C - V)(C + V_i)}$$

Our goal is to find the target speed $V_t$ when we know $C$, $V$ and $\gamma$. For $V_t$, (6) becomes:

$$V_t = \frac{C(1 - \gamma) + V(1 + \gamma)}{C(1 + \gamma) + V(1 - \gamma)} C$$

The second term of the denominator can be approximated to zero because it is very small compared to the first term of the denominator. In short,

$$V_t = V + \frac{1 - \gamma}{1 + \gamma} C$$  \hspace{1cm} (8a)$$

$$V_r = V_t - V = \frac{1 - \gamma}{1 + \gamma} C$$  \hspace{1cm} (8b)
Sensor user’s speed $V$ is separated, and the target speed or relative speed can be calculated immediately by calculating the time dilation $\gamma$ through the time dilation correlation.

IV. EXPERIMENTATION

A. Signal Processing

Fig. 4 shows the target speed measurement signal processing, and Fig. 5 shows the signal graphs at each part in the transmitter and receiver.

At the transmitter, Chua’s circuit [9], the well-known and the simplest chaotic signal generator provides a chaotic signal. The chaotic signal is input to the pulse position modulator (PPM) to generate a CPPM reference signal: Fig. 5 (a), for ultrasonic pulse transmission [5], [8].

The ultrasound receiver collects echoes that are returned to the target: Fig. 5 (c). Though thresholds can be applied to the collected analog signals to convert them to digital signals, a threshold is applied to the 40 kHz component of the FFT to further enhance noise rejection. The threshold is determined experimentally and is set slightly higher than the road noise collected during driving at 90 km/h. Fig. 5 (d) shows the FFT 40 kHz components and Fig. 5 (e) shows its binary digital signal.

Both binary signals $\psi_x$ and $\psi_y$ were sampled at a sampling rate of 100 kHz. The sampling rate of 100 kHz has a target speed resolution of 0.0062 km/h, which is sufficient for vehicle control applications. If the sampling rate is 10 kHz, the speed resolution would be 0.062 km/h. After sampling the binary signals, the dilation correlation was performed. As can be seen in Fig. 2, the peak position can be considered as the time dilation $\gamma$ of the echo signal, due to the Doppler effect. Once the time dilation $\gamma$ is obtained, the target speed or relative speed can be calculated according to (8a, 8b).

B. Measurement System

Fig. 6 shows a diagram of the hardware system. It contains an ultrasonic transmitter, an ultrasonic receiver, a signal conditioner and a microcontroller. Both the transmitter and the
receiver used a 40 kHz ultrasonic transducer. A microcontroller ‘National Instrument CompactRIO-9036’ was used to run ultrasonic transmitter operation and data acquisition. The microcontroller included a 1 MHz analog to digital converter (ADC) that samples 40 kHz ultrasound wave and a 1.33 GHz dual core CPU with a field programmable gate array (FPGA) module. The microcontroller collected ultrasound data and transferred to a computer. After collecting the data, signal processing was performed on the computer. The analog signal filter is a simple high-pass filter to remove DC components.

Fig. 7 shows the sensor part used in the experiment. An ultrasonic transmitter and a receiver are arranged side by side and a laser sensor is installed as a reference sensor to be compared with the ultrasonic measurement result.

C. Experimental Results

As shown in Fig. 8, two vehicles were moving. The preceding vehicle kept the speed constant for safety. The following vehicle speeds were varied to produce a relative speed. Both vehicles travel in the same direction and a sensor is installed on the following vehicle to measure the distance to the preceding vehicle and the speed of the preceding vehicle. Fig. 9 shows the following four speed values:

- Sensor user speed (dashed black line).
- The speed value obtained by differentiating the distance values measured by laser sensor (solid red line).
- The speed value obtained by differentiating the distance values obtained by the ultrasonic sensor time-of-flight (TOF) method [8] (dotted blue line).
- The speed value obtained using the proposed method in this paper (solid black line).

All target speed values were calculated by determining the relative speed and adding the user vehicle speed. The two error graphs show the error of the last two of the above values. Each error was calculated based on the value of laser sensor. The RMS errors are 2.39 km/h and 1.81 km/h, respectively. The proposed method, which can directly measure the target speed, shows that there is acceptably small error, while the distance value differential has a lot of error.

V. Conclusion

The proposed target speed measurement method using the time dilation correlation enables the Doppler effect to be analyzed in the time domain rather than frequency domain. This method has great advantages in a sampled signal processing such as the system of this paper. In general, the Doppler effect is analyzed in the frequency domain, and the sampling frequency should be several to several tens of times higher than the wave to be analyzed, to achieve the desired speed resolution. However, when analyzed in the time domain, the speed analysis can be performed at much lower sampling frequencies with the proposed method. Moreover, time scaling of analog signals could be difficult, but is relatively easy for digital single bit signals.

Experimental results show that it has less RMS error to obtain the target speed directly by the Doppler effect and the time dilation correlation, than to differentiate the distance obtained by time-of-flight (TOF) method. It allows to calculate the target speed with a simple and small calculation.

REFERENCES


