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Acceleration Measurement with a Trial On-board Recorder

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Abstract: Several preliminary measuring experiments with a trial on-board recorder were done in our recent studies for the on-board traffic accident recorder. The aim is to investigate the reproducibility of a locus of automobile. In this report, a method to find the correction factors to improve the reproducibility is mentioned. The method is based on the concept of complex spectral analysis.

Keywords: Acceleration measurement, on-board recorder, automobile, EDR, traffic accident.

1. Introduction

Recently, the practical use of various on-board recording devices that are activated when a traffic accident occurs has begun. The commercial models of such device and/or the automobiles equipped similar functions are about to increase also in Japan. The devices are called ”EDR” or other various names; ”ADR”, ”UDS”[1)], ”ADDR”[2)], ”Black Box” and so on. All of those are written ”**EDR**[†]” below.

Originally, EDR was developed mainly aiming at the study for safety device and/or the mechanism of traffic accidents in most cases. Although conventional major purposes are those, EDR has many other useful applications also. Because of that EDR records many kinds of information about the accident. Some of EDR can capture the video images[3)].

One of the useful applications is traffic accident reconstruction for the court. EDR can give valuable evidences for the trials of traffic accidents. For instance, the vehicle speed just before the collision has been estimated from the tire marks on the road surface formerly. Contrary to this, you can know the speed directly as a measured value by EDR which can record the speed pulse from the ECU[††]. Thus EDR will promote the improvement of the accuracy and reliability of accident reconstruction. Actually, some cases that the data which were acquired by EDR have been accepted as an evidence in the court exist in Germany and the US.

However, delicate cares are necessary when the recorded data are handled. The information includes measured physical values and the conditions of switches or driver’s operations. Comparing with that the on/off information of turn signal lamp is relatively easy to grasp as it is, especially it requires some analytical procedures to estimate the locus of vehicle body on an ordinary occasion. Then the analytical result is more or less away from actual locus in fact.

Under these situations, in order to use the information from EDR properly, we are investigating the reproducibility of a locus of vehicle body with the records of the acceleration. And several preliminary measuring experiments with a trial on-board recorder were done.

In this report, an expedient method to find the correction factors to improve the reproducibility is mentioned in the case of that measured data are dual axes acceleration and yaw angular rate. The method is based on the concept of complex spectral analysis.

[†] **E**vent **D**ata **R**ecorder [††] **E**ngine **C**ontrol **U**nit

2. Trial On-board Recorder

Since no regulations of EDR have been established yet in japan, the information to be recorded in the device are various and different from each other according to the developers. Excepting the simple built-in type recorder set in the air bag control module, most conventional EDR device can record the dual axis acceleration. And the information of the vehicle direction can be recorded also. Therefore, we think about the vehicle behavior as a plane motion.

By the way, it is desirable for EDR to be cheap as possible. Usually the performance of commercial model to be equipped on many automobiles is inferior to the measuring instruments for the laboratory use. Reflecting on these points, a trial on-board recorder to obtain the concrete data for surveying the reproducibility of locus was made of commercial discrete parts.

2.1 Configuration and measuring items

The trial device comprises the sensors, analog LPFs, two micro-controllers, data memories and a battery unit mainly. The measuring and recording of the acceleration and yaw rate of the vehicle can be done with this device alone. This device can measure the tree dimensional acceleration also. AD converters are the internal ADC of the micro-controller. The resolution of AD conversion is 12bits and the sampling rate is set to 1ksps at each channel. The cut-off frequency of the analog LPFs are 75Hz for the acceleration signal and 20Hz for the yaw rate signal. The digital filtering with the algorithm of moving averages is done after AD conversion. Sampling frequency of recorded data is 125Hz finally. Total data memory size is 128kbytes excepting the working memories.

2.2 Sensors

The trial on-board recorder has three sensors. Those are a triaxial acceleration sensor, an angular rate sensor and a temperature sensor. The specifications of two sensors are shown

Table 1: Details of the sensors

	Acceleration sensor	Rate gyro
Range	$\pm$2G	$0 \sim \pm$100deg/s
Sensitivity	1V/G	1mV/(deg/s)
Bandwidth	DC to 50 Hz	$>$ 10Hz
Bias	$+$2.5V	50% of Vdd
Vdd	$+5.00 \pm 0.25$V	$+5.00 \pm 0.25$V
Noise	1.0 mG rms	$<$ 1 mV rms

Table 2: Notation (1)

Symbols	Explanations [unit]
$\boldsymbol{a}_s(t)$, $\boldsymbol{a}_g(t)$	Acceleration [m/s^2]
$a_x(t)$, $a_y(t)$	Acceleration [m/s^2]
$\boldsymbol{v}_g(t)$, $\boldsymbol{v}_0$	Velocity [m/s]
$\boldsymbol{r}_g(t)$, $\boldsymbol{r}_0$	Displacement (Position) [m]
$\phi(t)$	Angular velocity (YAW) [rad/s]
$\theta(t)$, θ_0	Angle (Direction) [rad]

in Table.1. These are sillicon MEMs products. The temperature sensor is integrated on the micro-controller.

2.3 Problems

We started several preliminary measuring experiments with above trial on-board recorder. Then some problems come arise instantly. One of the important matters is that the reproductivity of vehicle's locus is disagreeable. So that, a method to compensate the mild drift or basic characteristics of each device is considered. A feature of this method is to be operable at the on-board situation.

3. Reproduction of a Locus

Taking the sensor's posture into account, the vehicle's locus are given after the twice integrations of acceleration value. The collision phenomena were omitted from the subjects of study in this time.

Using the time functions $a_x(t)$ and $a_y(t)$ of the acceleration, the complex signal representation $\boldsymbol{a}_s(t)$ of the acceleration data is defined by the following equation [4].

$$\boldsymbol{a}_s(t) = a_x(t) + a_y(t)\boldsymbol{i} \tag{1}$$

The usage of the symbols is shown in Table.2. The real axis equal to the X axis of the sensor. The imaginary axis equal to the Y axis of the sensor. The acceleration $\boldsymbol{a}_s(t)$ is expressed on the sensor coordinates. Since the sensor coordinate system is not the inertial system, it should be converted to the representation $\boldsymbol{a}_g(t)$ on the ground coordinate system by using the automobile's direction $\theta(t)$.

$$\boldsymbol{a}_g(t) = \boldsymbol{a}_s(t)\boldsymbol{e}^{\theta(t)\boldsymbol{i}} \tag{2}$$

Table 3: Notation (2)

Symbols	Explanations [unit]
$D_x(t)$, $D_y(t)$, $D_\phi(t)$	Recorded data [v]
α_1, α_2, α_{1c}, α_{2c}	Scale factor [m/s^2/v]
α_3, α_{3c}	Scale factor [rad/s/v]
β_1, β_2, β_3, β_{1c}, β_{2c}, β_{3c}	Zero offset [v]
θ_{ta}	Angle (at $t = t_a$) [rad]
$k_{\theta e}$	Fitting angle error [rad]
$k_{\alpha 1}$, $k_{\alpha 2}$, $k_{\alpha 3}$, $k_{\beta 1}$, $k_{\beta 2}$, $k_{\beta 3}$	Correction factor [-]
$v_x(t)$, $v_y(t)$	Velocity [m/s]

The automobile's direction $\theta(t)$ can be estimated from the time function $\phi(t)$ of the YAW rate value as follows.

$$\theta(t) = \int_0^t \phi(\tau)d\tau + \theta_0 \tag{3}$$

Here, θ_0 is the initial value of the direction. The vehicle's velocity $\boldsymbol{v}_g(t)$ and the displacement $\boldsymbol{r}_g(t)$ are calculated from above $\boldsymbol{a}_g(t)$ by the operation of integration as followings.

$$\boldsymbol{v}_g(t) = \int_0^t \boldsymbol{a}_g(\tau)d\tau + \boldsymbol{v}_0 \tag{4}$$

$$\boldsymbol{r}_g(t) = \int_0^t \boldsymbol{v}_g(\tau)d\tau + \boldsymbol{r}_0 \tag{5}$$

Here, $\boldsymbol{v}_0$ and $\boldsymbol{r}_0$ is the initial value. The time function $\boldsymbol{r}_g(t)$ described in this way is just the locus that we remark.

4. Improvement of Reproducibility

The usage of the symbols below is shown in Table.3. The acceleration values $a_x(t)$ and $a_y(t)$ at the time t are found from the recorded data $D_x(t), D_y(t), D_\phi(t)$ as followings.

$$a_x(t) = \alpha_1(D_x(t) + \beta_1) \tag{6}$$

$$a_y(t) = \alpha_2(D_y(t) + \beta_2) \tag{7}$$

$$\phi(t) = \alpha_3(D_\phi(t) + \beta_3) \tag{8}$$

Here, $D_x(t), D_y(t)$ are the acquired acceleration data. $D_\phi(t)$ is the acquired YAW rate data. Although these data are discrete values by AD conversion actually, let those values be the analog signal for convenience. $\alpha_1 \sim \alpha_3$ are scale factors. $\beta_1 \sim \beta_3$ are sensor's zero offset values. Those are the values written on the sensor manufacturer's calibration data sheet.

Where, many factors effect the recorder system, so that the acquired data includes some errors. Therefore, the calculated locus fails to match the true one when the values on the sensor's data sheets are used as it is.

4.1 Correction model

Assuming the following model that the major error factors are reflected in above values $\alpha_1 \sim \beta_3$ of Eq.(6) $\sim$ Eq.(8),

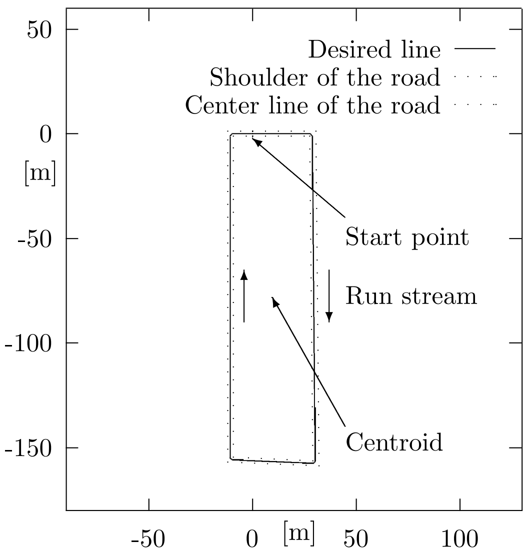

Figure 1: Test path

more proper parameters $\alpha_{1c} \sim \beta_{3c}$ are given by introducing the correction factors $k_{\alpha 1} \sim k_{\beta 3}$ to compensate the error.

$$\begin{cases} \alpha_{1c} = k_{\alpha 1}\alpha_1 \\ \beta_{1c} = k_{\beta 1}\beta_1 \end{cases}, \begin{cases} \alpha_{2c} = k_{\alpha 2}\alpha_2 \\ \beta_{2c} = k_{\beta 2}\beta_2 \end{cases}, \begin{cases} \alpha_{3c} = k_{\alpha 3}\alpha_3 \\ \beta_{3c} = k_{\beta 3}\beta_3 \end{cases}$$

These correction factors can be estimated from the measuring data with the following test traveling.

4.2 Traveling pattern

The test traveling pattern to estimate the above factor $k_{\alpha 1} \sim k_{\beta 3}$ is required to satisfy these conditions.

- The final point of the path is the same as the start point, namely the traveling path must be closed. And it draws the single loop. A centroid of the path should be known.
- The path should include no ramp at any part of it.
- Starting from stopping condition, the automobile must stop on the final point at the end of the traveling, and keeps stop state a while. The direction of the automobile at the final point must be same at the starting point.
- The recording function must be kept in active a while under the stopping condition.

For instance, a sample travelling pattern we are attempting now is shown in Fig.1. The trial on-board recorder was installed as to be that the direction of the sensor axes are along to the longitudinal and transverse direction of the vehicle. It is the road in a residential suburb. The road surface is relatively flat and smooth. And the test path includes no remarkable slope. The test vehicle started from rest condition and run the loop. Finally the test vehicle returns at the starting point and stops.

4.3 Estimation of the correction factors

From the YAW rate data Under the condition that the automobile is at rest while $t = t_a \sim t_b$, the $\theta(t)$ keeps a constant value θ_a. It appears at the final point of the test path.

$$\theta(t_b) = \int_{t_a}^{t_b} \alpha_{3c}(D_\phi(\tau) + \beta_{3c})d\tau + \theta_a = \theta_a \tag{9}$$

$$\therefore \ \beta_{3c} = -\frac{1}{t_b - t_a}\int_{t_a}^{t_b} D_\phi(\tau)d\tau \tag{10}$$

Nextly, the vehicle's direction revolves 2π rad with a loop traveling on above test pattern. Therefore, the following equation holds true when the traveling time is t_L.

$$\theta(t_L) = \int_0^{t_L} \alpha_{3c}(D_\phi(\tau) + \beta_{3c})d\tau + \theta_0 = \theta_0 + 2\pi \tag{11}$$

$$\therefore \ \alpha_{3c} = \frac{2\pi}{\int_0^{t_L} D_\phi(\tau)d\tau + \beta_{3c}t_L} \tag{12}$$

Since the values of integration of D_ϕ can be found numerically from the recorded data, the desired values α_{3c} and β_{3c} can be estimated by Eq.(12) and Eq.(10).

From the acceleration data Subsequently, the sensor coordinate system can be assumed the inertial system, if the automobile is at rest. The velocity of the vehicle is kept zero.

$$v_x(t_b) = \int_{t_a}^{t_b} \alpha_{1c}(D_x(\tau) + \beta_{1c})d\tau = 0 \tag{13}$$

$$\therefore \ \beta_{1c} = -\frac{1}{t_b - t_a}\int_{t_a}^{t_b} D_x(\tau)d\tau \tag{14}$$

$$v_y(t_b) = \int_{t_a}^{t_b} \alpha_{2c}(D_\phi(\tau) + \beta_{2c})d\tau = 0 \tag{15}$$

$$\therefore \ \beta_{2c} = -\frac{1}{t_b - t_a}\int_{t_a}^{t_b} D_y(\tau)d\tau \tag{16}$$

Since the values of integration of D_x and D_y can be found numerically from the recorded data, the desired values β_{1c} and β_{2c} can be estimated by Eq.(14) and Eq.(16).

From a viewpoint of spectral analysis By the way, writing the complex Fourier coefficients of $\boldsymbol{a}_g(t)$ and $\boldsymbol{r}_g(t)$ in an interval $t_a \sim t_b$ with $\boldsymbol{A}_g(f)$ and $\boldsymbol{R}_g(f)$, the relationship of the DC component of $\boldsymbol{a}_g(t)$ and $\boldsymbol{r}_g(t)$ are as next.

$$\boldsymbol{R}_g(0) = \frac{1}{t_b - t_a}\int_{t_a}^{t_b} (\frac{1}{2}\boldsymbol{A}_g(0)\tau^2 + c_1\tau + c_2)\boldsymbol{e}^{-2\pi 0\tau}d\tau \tag{17}$$

Here, considering above test pattern, it becomes that $t_a = 0$, $t_b = t_L$, $C_1 = 0$, $c_2 = 0$. Then Eq.(17) is as follows.

$$\boldsymbol{R}_g(0) = \frac{1}{t_L}\int_0^{t_L} \frac{1}{2}\boldsymbol{A}_g(0)\tau^2 d\tau = \frac{t_L^2}{6}\boldsymbol{A}_g(0) \tag{18}$$

On the other hand, $A_g(0)$ can be written as next.

$$\boldsymbol{A}_g(0) = \frac{1}{t_L}\int_0^{t_L} \boldsymbol{a}_g(\tau)\boldsymbol{e}^{-2\pi 0\tau}d\tau \tag{19}$$

Where $\boldsymbol{R}_g(0)$ is equal to the centroid $\boldsymbol{L}_{DC}$ $(= L_{DCX} + L_{DCY}\boldsymbol{i})$ of the test path. So that, next relationship are given from Eq.(18), Eq.(19) and Eq.(2).

$$\int_0^{t_L} \boldsymbol{a}_s(\tau)\boldsymbol{e}^{\theta(\tau)\boldsymbol{i}}d\tau = \frac{6\boldsymbol{L}_{DC}}{t_L} \tag{20}$$

Furthermore, using Eq.(6) and Eq.(7), next simultaneous equations are given.

$$\int_0^{t_L} \alpha_{1c}(D_x(\tau)+\beta_{1c})\cos\theta(\tau) - \alpha_{2c}(D_y(\tau)+\beta_{2c})\sin\theta(\tau)d\tau = \frac{6L_{DCX}}{t_L} \tag{21}$$

$$\int_0^{t_L} \alpha_{1c}(D_x(\tau)+\beta_{1c})\sin\theta(\tau) + \alpha_{2c}(D_y(\tau)+\beta_{2c})\cos\theta(\tau)d\tau = \frac{6L_{DCY}}{t_L} \tag{22}$$

Solving this simultaneous equations, α_{1c} and α_{2c} can be described by a computable values.

$$\alpha_{1c} = \frac{6}{t_L}\left(\frac{L_{DCX}h_{2c} + L_{DCY}h_{2s}}{h_{1c}h_{2c} + h_{1s}h_{2s}}\right) \tag{23}$$

$$\alpha_{2c} = \frac{6}{t_L}\left(\frac{L_{DCY}h_{1c} - L_{DCX}h_{1s}}{h_{1c}h_{2c} + h_{1s}h_{2s}}\right) \tag{24}$$

Here, h_{1c}, h_{1s}, h_{2c} and h_{2s} stand for these integrations.

$$h_{1c} = \int_0^{t_L}(D_x(\tau)+\beta_{1c})\cos\theta(\tau)d\tau \tag{25}$$

$$h_{1s} = \int_0^{t_L}(D_x(\tau)+\beta_{1c})\sin\theta(\tau)d\tau \tag{26}$$

$$h_{2c} = \int_0^{t_L}(D_y(\tau)+\beta_{2c})\cos\theta(\tau)d\tau \tag{27}$$

$$h_{2s} = \int_0^{t_L}(D_y(\tau)+\beta_{2c})\sin\theta(\tau)d\tau \tag{28}$$

From above values $\alpha_{1c} \sim \beta_{3c}$, the correction factors $k_{\alpha 1} \sim k_{\beta 3}$ can be estimated as follows.

$$\left\{\begin{array}{l} k_{\alpha 1} = \frac{\alpha_{1c}}{\alpha_1} \\ k_{\beta 1} = \frac{\beta_{1c}}{\beta_1}\end{array}\right., \left\{\begin{array}{l} k_{\alpha 2} = \frac{\alpha_{2c}}{\alpha_2} \\ k_{\beta 2} = \frac{\beta_{2c}}{\beta_2}\end{array}\right., \left\{\begin{array}{l} k_{\alpha 3} = \frac{\alpha_{3c}}{\alpha_3} \\ k_{\beta 3} = \frac{\beta_{3c}}{\beta_3}\end{array}\right.$$

In the actual calculation, numerical integrations will be done with the measured data of discrete values. And the most formulas in this section are the computations of average value.

4.4 Remarks

There are relatively many reports about the reproducibility on the test courses and the ability to record the impulsive acceleration of the crash. However, those are not enough to the accident reconstruction for the court. Because the reproducibility of vehicle behavior during pre- and/or post-crash term is a important thing also. It should be required to get the concerete data on the public road of various condition. These results will be utilized for putting the on-board accident recorder to practical use in the traffic accident reconstruction properly. At the time to use the above method, several arrangements are need in the test procedures. One is that the calculation will be done by backward from the final rest point.

Spectral analysis The ways of thinking based on spectral analysis may be effective at the scene to classify the vehicle motion and the vibration. The chassis vibration may remain less than about 0.1m displacement in general. On the other hand, in the accident reconstruction work it is desired that the difference of about 0.1m degree can be clearly distinguished, if it is possible. For instance, line markings on the road or the width of tires for automobiles would be discussed around 0.1m order. Namely, the final goal is to enable the discussion on 0.1m order. However, there is yet no remarkable achievement at present. In this sense, we are looking for a clue to this problem using the concept of spectral analysis.

Error of fitting angle If it is possible to discriminate the section of straight advance in the test path from YAW rate information, the error of fitting angle of the acceleration sensor on a horizontal plane can be considered. Because of that the automobile goes straight ahead in such section. It can be drawn by observing the profile of compensated $\phi(t)$.

5. Conclusion

A method to find the correction factors to improve the reproducibility was introduced in our recent studies of EDR. The validity of this method is under the examine through the experimental test. Presently, we are investigating the reproducibility of automobiles on public roads of various conditions for accident reconstruction.

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