Dual sampling rate digital signal processing for low speed vehicle tests

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Abstract

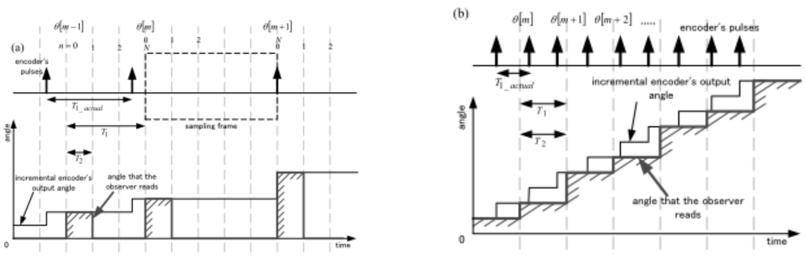
Train running tests are significant to verify vehicle performances. Since the place for such tests are often limited, such tests are executed in low speed, even when a pulse encoder of a train is usually coarse. A measured speed signal has, therefore, considerable delay, large sample time and is often noisy. An acceleration signal can be simultaneously measured with substantially small delay and sampling time. A smart signal processing for combining the two different signal may be useful to improve the quality of such measurements. This paper explains a proposal of the signal processing based on the theory of current type dual-rate sampling state estimator, and shows the advantage based on an experimental case study using real data from vehicle test measurements in Tokyo by drawing time-acceleration, time-speed, position-speed and speed-acceleration profiles.

Keywords: electric train, measurement, dual-rate sample observer, state estimation, speed sensor, pulse encoder

1 Introduction

It is significant to record time, position, speed and acceleration precisely in a vehicle running test. The main signal from rotating wheel axis is train speed. Ordinary rotary encoders in electric trains are course. Especially, it causes the problem of bad resolution of the speed signal and considerable dead time, when the train speed is low. It often happens in a limited running test in a depo as shown in Figure 1. Time charts of the position signals produced from an coarse encoder are schematically illustrated in Figure 2. The train performance can be directly measured if its acceleration and deceleration are measured. However, when one puts an acceleration sensor on a train body, the dynamics between bogies and the body affects the measurement and the output of the acceleration sensor is often noisy. An example of acceleration sensor signal is shown in Figure 3.

Figure 1: An image of a test run of a train in a depo.



(a) At low speed (b) At high speed

Figure 2: Position sensing based on coarse pulses from rotating wheel. (The pulses are obtained from a pulse encoder embedded in traction drive control system.)

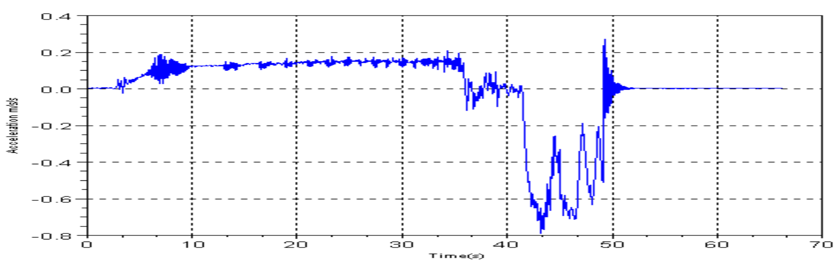


Figure 3: Measured acceleration signal from a short test run in Figure 1 .

2 Speed estimation and dual-rate sample state observer

Authors proposed a method to estimate speed as well as external force using intermittent position signal from a coarse pulse encoder based on dual sample-rate digital state observer using knowledge of plant dynamics, and verified its usefulness with an experiment of active feedback motion control of oscillating two-mass mechanical system in Kovudhikulrungsri *etal*[1]. The "dual sample-rate" means the handling of the following two different period T_1 and T_2: T_1 is the long period between two consecutive encoder pulse depending on the rotor speed, whereas T_2 is the short constant sample period of a related digital signal processor or a CPU. The proposed observer design method mathematically guarantees the stability of state estimation. Especially in the current type digital observer, one can guarantee identical stable observer pole locations both on the two *Z*-domains of different sampling times T_1 and T_2. This paper shows an application of this sophisticated digital state estimation to a short distance slow vehicle test run in the following case studies. The major sensed information is speed signal of a rotating un-motored axis obtained every 750msec.

3 Case studies

All the data post-processings in this chapter have been implemented based on SCILAB, a famous free numerical software supplied by a French national research institute *INRIA*[2] . The details are informed in Campbell *etal*[3].

3.1 Speed and acceleration data measured directly

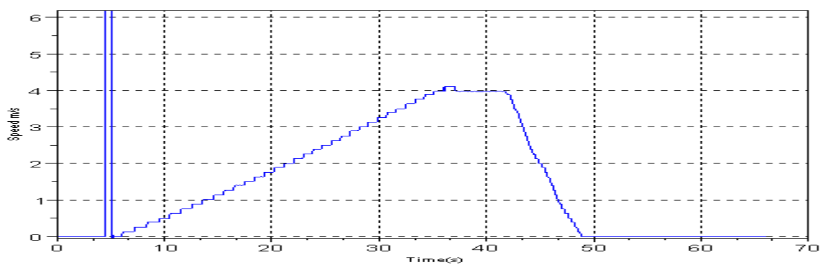


Figure 4: Direct output signal from a speed sensor.

The speed sensor output is obtained every 750msec. When the vehicle speed is low, considerable error can be caused in the speed sensing. One should pay attention to the fact that the measured speed signal substantially includes a a considerable dead time of 375msec in average. Figure 4 shows an example of the speed signal measured directly in our vehicle test. For an analysis, we use also the acceleration signal shown in Figure 3.

3.2 Data post processing using a low pass filter

A simple countermeasure for smoothing the step-wise/ noisy signals to apply a low-pass filter, although the considerable delay will be added to the signals. Figures 6 and 7 show the speed and acceleration data filtered by a second-order Butterworth filter whose equivalent time constant is 1.0sec. The obvious error at low speed has been intentionally removed in the date-processing for Figure 6.

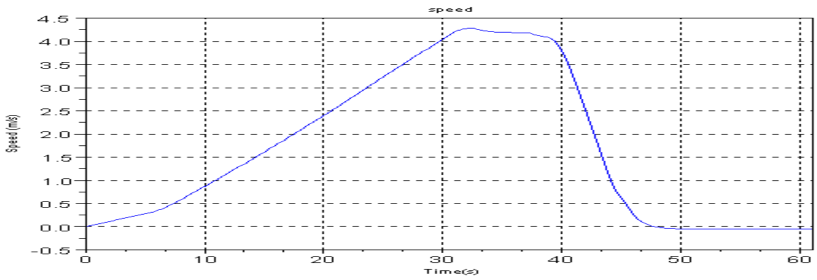


Figure 6: Speed signal filtered through a second-order Butterworth low pass filter with an equivalent time constant of 1.0sec.

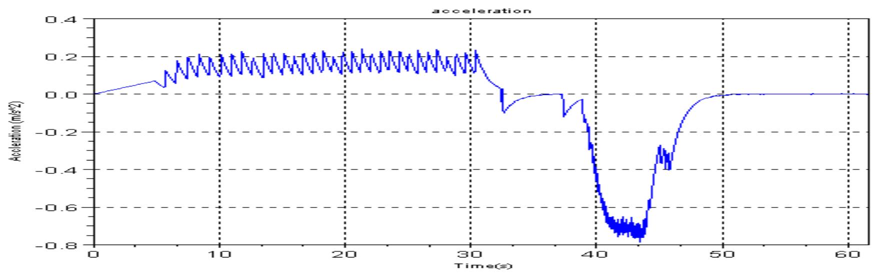


Figure 7: Measured acceleration signal filtered through a second-order Butterworth low pass filter with an equivalent time constant of 1.0sec.

The acceleration signal in Figure 7 seems still oscillatory. By integrating the signal in Figure 6, relative position can be calculated as in Figure 8. By combining the information on speed and the relative position, the run-curve is drawn in Figure 9. Also the speed-acceleration locus is drawn in Figure 10 may be useful for evaluating the train performance. However an additional acceleration sensor is necessary for this evaluation and the acceleration plot tends to be oscillatory even after the low pass filtering.

3.3 Data post processing using speed and acceleration signals based on dual-rate sample digital observer---unsuccessful trial

When one can use the information from acceleration sensor, the signal can be used as input to the state estimator substituting motor current in the dual-sample rate observer described in Kovudhikulrungsri *etal*[1]. Numerical integration of the acceleration signal is compared with measured speed signal every T_1=750msec, and error correction is executed every T_1.For keeping the Shonnon's sample theorem, the equivalent time constant of the state estimator is selected slightly larger than $2T_1$. The results of a case study are shown in 11 and 12.

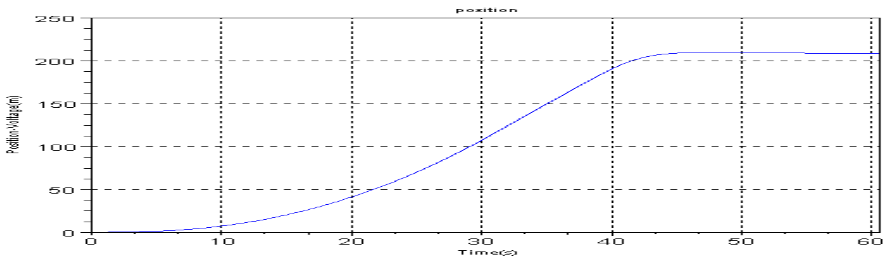


Figure 8: Position as an integral of speed signal filtered through a second-order Butterworth low pass filter with an equivalent time constant of 1.0sec in Figure 6.

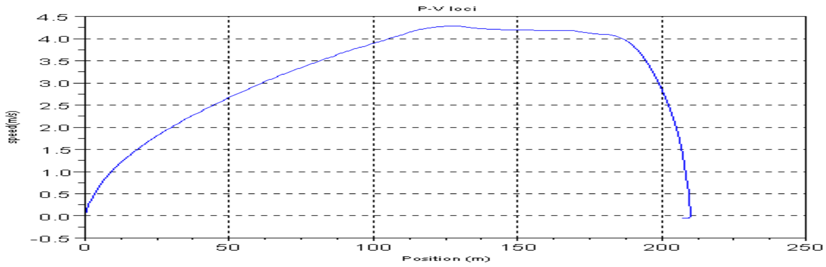


Figure 9: Run-curve plotted from position information in Figure 8 and the speed signal filtered through a second-order Butterworth low pass filter with an equivalent time constant of 1.0sec in Figure 6.

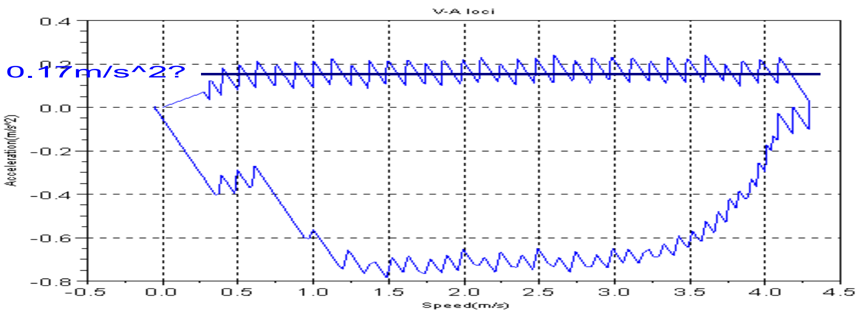


Figure 10: Speed-acceleration plot from speed information in Figure 6 and the acceleration signal filtered through a second-order Butterworth low pass filter with an equivalent time constant of 1.0sec in Figure 7.

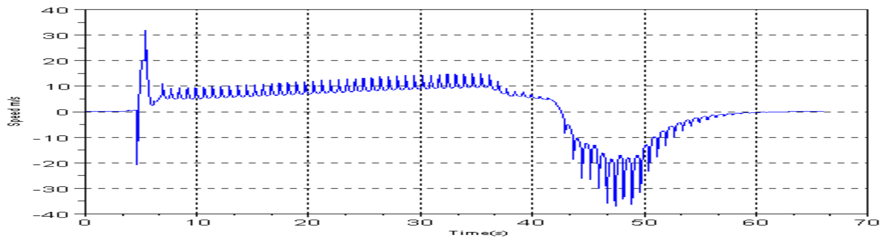


Figure 11: Speed plot corresponding to Figure 5 estimated by the dual- sampling rate observer from the acceleration in Figure 4 as an input signal and the speed in Figure 5 as an output. The equivalent rime constant of the observer is set to 1.6sec.

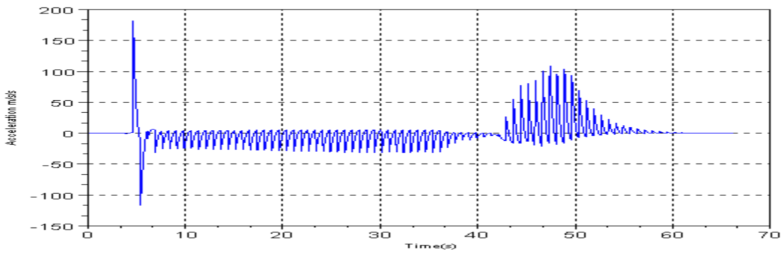


Figure 12: Acceleration plot corresponding to Figure 4 estimated by the dual-sampling rate observer from the acceleration in Figure 4 as an input signal and the speed in Figure 5 as an output. The equivalent rime constant of the observer is set to 1.6sec.

An example of the SCILAB code for this state estimation is as follows. The mathematical description of the state estimation here is skipped, since it is based on the description in Kovudhikulrungsri *etal*[1] .

```
// The part of Dual Sample-Rate Digital State Observer
T0=0.4; // Time constant of LPF for acceleration
Te=1.6;// Equivalent time constant of state estimator
//Calculation of estimator gain L
  p=poly([1, Te/2, Te^2/2, Te^3/8], 's','coeff')// Three-order Kessler form
s_poles=roots(p); z_poles=exp(s_poles*T1);
//System definition
A=[0.0 1.0 0; 0.0 0.0 1.0; 0.0, -2.0/T0^2 -2.0/T0]; B=[0.0; 0.0; 2.0/T0^2];
C=[1.0 0.0 0.0]; D=[0]; x0=[0.0; 0.0; 0.0];
A1=expm(A*T1)
A2=expm(A*T2)
//[sl2]=syslin("d", A2, B, C, D, x0);   //    SS-System definition
// Observer design:
K=ppol(A1', C', z_poles); L=K'
x_est(:,1)=x0;
 [msize,nsize]=size(chdata); u(1)=v7*(chdata(1,3));
```

```
for ii=1:msize-1
u(ii+1)=v7*(chdata(ii+1,3));
  fl=1-find(modulo(ii-3,N)~=0);
x_est(:,ii+1)=A2*x_est(:,ii)+B*u(ii+1)+fl*L*(v5*chdata(ii+1,2)-C*A2*x_est(:,ii));
end
```

Unfortunately the estimation was not very successful. The curves in Figures 11 and 12 contain relatively large oscillatory components. Since there are inherent mismatches between sensings of the speed and he acceleration, the error-correction at every T_1 is large. Therefore, the state-estimation just using the speed information shall be tried in next section.

3.4 Data post processing based on dual-rate sample digital observer

The following homogeneous linear state equation is assumed here:

$$\frac{d}{dt}\begin{bmatrix}\hat{v}\\ \hat{a}\\ \hat{\dot{a}}\end{bmatrix} = \frac{d}{dt}\begin{bmatrix}\hat{x}_1\\ \hat{x}_2\\ \hat{x}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & -\frac{1}{\tau}\end{bmatrix}\begin{bmatrix}\hat{x}_1\\ \hat{x}_2\\ \hat{x}_3\end{bmatrix} \quad (1)\,.$$

The dual rate observer successively calculate the solution of this homogeneous dynamic equation from an assumed initial condition at every T_2 = 50msec and the speed signal from a rotary encoder corrects the $\hat{x}_1$ at every $T_1 = 750\text{msec} = 15 \times T_2$. The continuous differential equation is converted to digital difference equation. The two different digital system matrices are prepared for the dual sampling rate digital calculations: $A_{D1} = \exp(A_C T_1)$ and $A_{D2} = \exp(A_C T_2)$. By giving the equivalent time constant T_e , the third-oder Kessler's Canonical form in Kessler[4] specifies three poles s_1, s_2, and s_3 on the continuous S-domain. The corresponding digital poles z_1, z_2 and z_3 on the Z-domain of sample time T_1 are calculated as $z_i = e^{s_i T_1}$, where i=1, 2 , and 3, respectively.

Now, the observer gain matrix L is determined so that the eigne values of the system matrix of the observer (A_1-LC) are z_1, z_2, and z_3. The current type digital observer of sampling time T_2 is derived by useing this L as follows.

$$\hat{\mathbf{x}}_n = A_{D2}\hat{\mathbf{x}}_{n-1} + Bu_n + L\left(\breve{y}_n - CA_{D2}\hat{\mathbf{x}}_{n-1}\right) \quad (2)$$

$$\breve{y}_n = \begin{cases} y_n & \text{if } n = \dfrac{T_1}{T_2} \\ CA_{D2}\hat{\mathbf{x}}_{n-1} & \text{else} \end{cases} \quad (3)$$

The Scilab-functions find and modulo are used for choosing the timing of correcting estimated state variables by the measured speed signal in (3). Since the original dynamic equation (1) is homogeneous, the input vector in (2) is set to zero in the following code.

The SCILAB code for the dual sample-rate state observer is as follows.

```
// State observer
tau=T1/3;//
Te=1.6;// Equivalent time constant of state estimator /Calculation of
estimator gain L
  p=poly([1, Te/2, Te^2/2, Te^3/10], 's','coeff')// Third-order Manabe form
s_poles=roots(p); z_poles=exp(s_poles*T1);
//System definition
A=[0.0 1.0 0.0; 0.0 0.0 1.0; 0.0 0.0 -1.0/tau]; B=[0.0; 0.0; 0.0];
C=[1.0 0.0 0.0; 0.0 1.0 0.0]; D=[0]; x0=[0.0; 0.0; 0.0];
A1=expm(A*T1)
A2=expm(A*T2)
// Observer design:
K=ppol(A1', C', z_poles); L=K'
x_est(:,1)=x0;

 [msize,nsize]=size(chdata);
for ii=1:msize-1
   fl=1-find((modulo(ii,N)~=0)| (ii<718 & ii> 701) );//pulse selection and initial
error elimination from 35-s5.9msec
x_est(:,ii+1)=A2*x_est(:,ii)+L*L_select*([v5*chdata(ii+1,2); v7*chdata(ii+1,3)]
-C*A2*x_est(:,ii));
end
```

Since the estimator uses no input signals, the definition of the input matrix *B* is different from previous case study. The Figures 13-16 show that this post-processing gives useful information of acceleration, speed and position just by using measured coarse speed signal. The estimator pole location in an unit cycle is shown in Figure 14. For the stable estimation, you must carefully choose the equivalent time constant of the estimator. Figure 17 shows the consequent pole locations designed through the careful choice of equivalent time constant and Kessler's Canonical form proposed in Kessler[4].

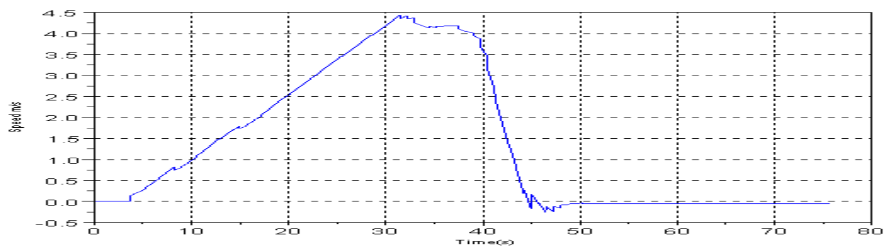


Figure 13: Speed plot corresponding to Figure 5 estimated by the dual- sampling rate observer from zero input signal and the speed in Figure 5 as an output. The equivalent rime constant of the observer is set to 1.6sec.

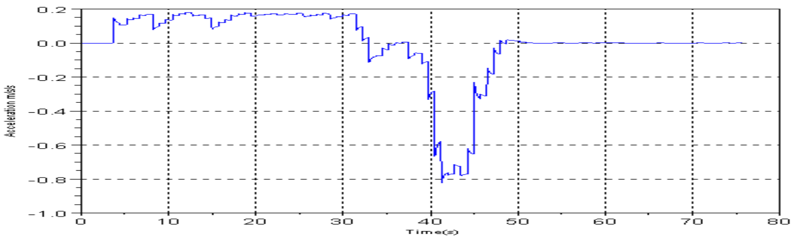


Figure 14: Acceleration plot corresponding to Figure 4 estimated by the dual-sampling rate observer from zero input signal and the speed in Figure 5 as an output. The equivalent rime constant of the observer is set to 1.6sec.

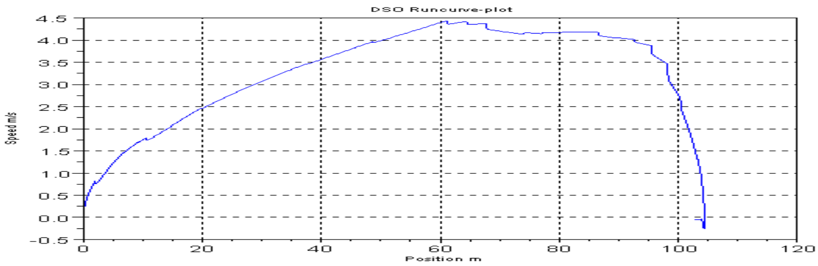


Figure 15: Run-curve corresponding to Figure 9 from the speed and integral of the speed in Figure 13.

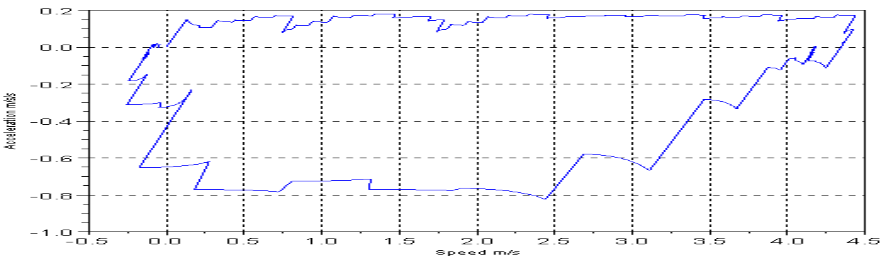


Figure 16: Speed-acceleration plot corresponding to Figure 10 from speed information in Figure 13 and the acceleration signal in Figure 14.

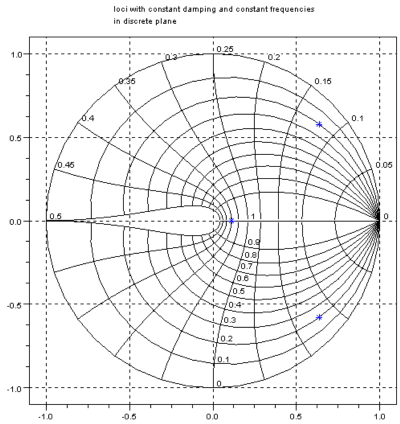


Figure 17: Pole location of the dual sample-rate observer, whose equivalent rime constant of the observer is set to 1.6sec, i.e., slightly larger than twice of T_1.

4 . Conclusions

The case studies of low-speed train test run in a depo shows that the dual sampling rate digital state observer proposed in [1] can estimate acceleration, speed and relative position signals from a speed signal measured from a coarse pulse encoder with its dead time of 375 msec in average and with interval of 750msec. If the encoder pulses can be directly used, the digital state estimation can be substantially better as described in [1]. This post-processing method can be comprehensively applicable to any train train test runs, since the mathematical basis is established and the theoretical formulation is fully open. Furthermore, the implementation is easy by using generic free numerical tools, *e.g.,* Scilab as shown in these case studies.

References

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