# On Advantages of High Frequency Sampling of Accelormeter for Time Integration and Time Synchronization

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This paper presents basic studies of possible advantages when sampling rate is increased up to 1,600[Hz] or 2,000[Hz] for an accelerometer. The advantages are i) accurate time integration of acceleration data so that displacement or velocity can be numerically calculated, and ii) time synchronization among sensors by comparing their waveforms which are observed with higher temporal resolution. Shaking table experiments are made to compare syntheses displacement from measured acceleration with measured displacement, and taking time synchronization of three sensors which observe actual earthquake is made. It is shown that while it fairly contributes to increase the accuracy of sampling rate, high sampling rate time leads to easy time synchronization of measured data.

***Key Words :*** *Quick inspection after earthquake, Accelormeter, High rate sampling, Time integration, Time synchronization*

## 1. NTRODUCTION

It is advantageous if quick inspection is made for structures which are hit by strong ground motion; inspection based on advanced sensing will be substitute for human eyes. An objective of such sensor-based inspection[1-3)] is to monitor seismic structure responses in aftershocks. Conditions of a shaking table experiment would be ideal state for monitoring; a set of sensors are installed to measure various structure responses with suitable time synchronization being taken so that mode shapes and response functions are determined.

Cost is a major problem[2)] to realize the ideal monitoring for actual structures; the price of sensors is still expensive and taking time synchronization among sensors needs extra devices such as wirelss network[4)]. To solve this problem, the authors have been studying development of a smart sensor. The smart sensor is an accelerometer which outputs displacement and velocity and does not need special devices for time synchronization. As long as the authors have surveyed, a concept of the smart sensor is new to the field of structure sensing.

To develop such a smart sensor, basic investigation is made regarding to the sampling rate. It is expected that as the sampling rate becomes higher, time integration[5)] of acceleration results in more accurate computation of displacement or velocity, and easy time synchronization is taken by precisely finding the arrival of strong ground motion which is observed with higher temporal resolution.

The contents of this paper are as follows: The two objectives of increasing the sampling rate are explained in Section 2. The accuracy of integrating acceleration measured at higher sampling rate is studied in Section 3, and the time synchronization which takes advantage of high sampling rate is proposed in Section 4. Concluding remarks are made in Section 5.

## 2. OBJECTIVES OF INCREASING SAMPLING RATE

In general, actual sampling rate of a sensing device is higher

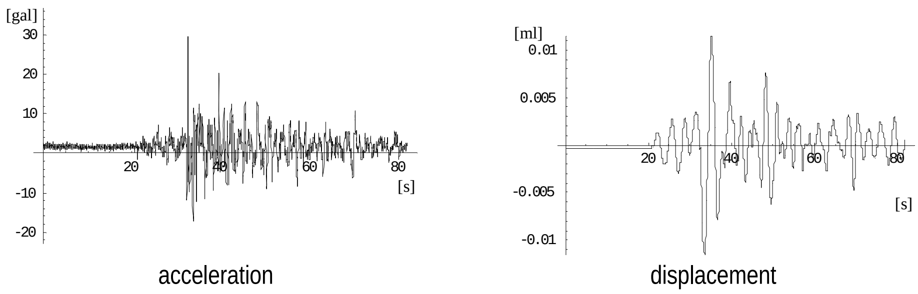



Figure 1. Measured data for Case 2.

than output rate of measured data; outputting rate is reduced by an A/D converter. This reduction is necessary when data storage or transmission is limited. Similarly, it is an A/D converter that determines the data length of output. The data length must be minimized, as well, for limited data storage or transmission.

With the development of information technology, a better A/D converter and a larger data storage are manufactured with lower price. Thus, while highest sampling rate is not needed for structure monitoring, it is not technically impossible to have higher sampling rate and longer data length.

There will be several possible applications when the sampling rate is increased. For an accelerometer, one application is time integration, i.e., numerical calculation of measured acceleration to calculate velocity or displacement. The magnitude of errors in time integration will be decreased at higher sampling rate; as explained later, errors due to white noises of measurement is reduced as more data are used for time integration. Another application is time synchronization, i.e., time series data measured by plural sensors share the same time. Higher sampling rate means finer temporal resolution of the data, and hence the occurrence of an event can be caught more accurately. Easy time synchronization will be taken by finding a suitable time shift for each sensor so that the event occurrence is at the same instance.

## 3. TIME INTEGRATION

It is principally possible to integrate acceleration time series twice to calculate displacement. Due to errors in measurement, however, high accuracy cannot be expected for the synthesized displacement. For instance, base alignment is needed for the measured acceleration to get rid of a quadratic or linear term. Measurement errors depend on frequency. Even though there are numerous filtering schemes proposed, accurate time integration remains a difficult task.

Measurement errors are caused by many factors such as device noises and limitation of digital data. On a statistical view-point, the errors obey normal distribution with zero mean. Since time integration is regarded as weighted summing, it is expected that as the sampling rate becomes higher, the effects of the device noises on time integration tend to decrease. The measurement errors due to the limited data length are suppressed, just by increasing the data length in converting analog data to digital values.

There is a trade-off for increasing the sampling rate and the data length. That is, the accuracy is improved but the cost becomes higher as the sampling rate and the data length increase. Thus, it is important to examine the accuracy of time integration, changing the sampling rate and the data length, in order to find the most suitable measurement setting.

To this end, we carry out a simple test for an acidometer prototype which has 1,600 Hz sampling rate and 24 bit data length; the acceolormeter is a severo-MEMS type. The prototype is put on a shaking table, and displacement of the table is measured by a laser displacement meter. Virtual acceleration data with lower sampling rate or shorter data length are generated. Displacement synthesized from actual and virtual data is compared with the measured displacement.

The discrete Fourier transform (DFT) is applied for time integration; a band-pass filter between 20 and 0.1 Hz is used, so that there are no errors involved in numerical calculation; this band pass filter is chosen in view of the servo-type MEMS acceloremter that is used in the prototype. Even though the DFT is computationally expensive filtering schemes, such as Simpson's method or Butterworth's scheme, are not used. While these schemes are less computationally expensive and applicable to real-time processing, errors are included in the amplitude and phase for higher frequency components.

The procedures of generating the virtual acceleration data are summarized as follows:

1) Convert the measured acceleration data expressed in real number to integer which is output from an A/D converter.
2) Reduce the sampling rate by using average values; an average is taken for a fixed time interval.
3) Reduce the data length by dropping lower bits in the original data.

The sampling rate and the data length of the virtual data are 200 or 100 Hz , and 20 or 16 bits; see Table 1.

Three cases are studied in the experiment; Case 1 is input of a

Table 1. Sampling rate and data length of actual and virtual data.

| | |
|---|---|
| sampling rate [Hz] | 1,600, 200, 100 |
| data length [bit] | 24, 20, 16 |

harmonic wave of 1 Hz, and Cases 2 and 3 are input of measured acceleration time series. As a typical example, this paper focuses the analysis of the result of Case 2. In Figs 1, the measured acceleration and displacement are presented.

The displacements which are synthesized from the virtual data are shown in Figs. 2; graphs in the top, middle and low rows are for the sampling rate of 1,600, 200 and 100 Hz, and graphs in the left, center and right columns are for the data length of 24, 20 and 16 bits. The wave form is similar in shape for 9 graphs, but the amplitude is different. As the sampling rate or the date length is decreased (i.e., from the top to the down or from the left to the right), the waveform appears altered; harmonic waves prior to the arrival, which are due to the DFT, becomes larger.

The similarity in the wave form and the difference in the amplitude are observed for other cases. In Case 1, which uses a harmonic

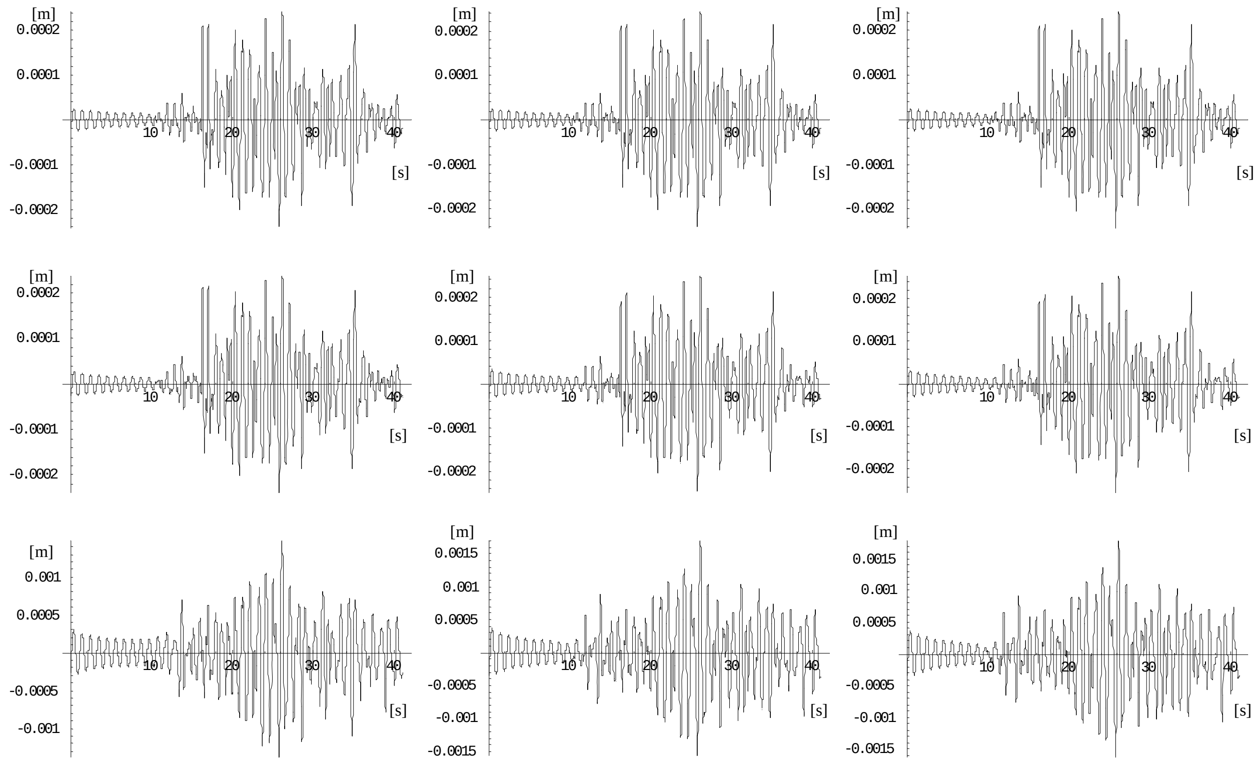
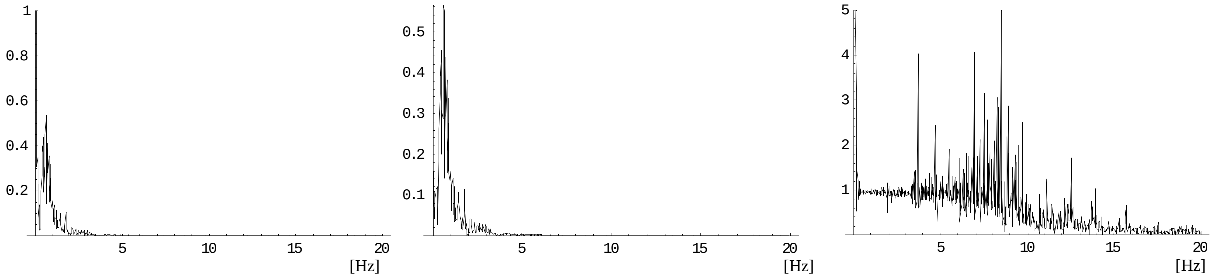



Figure 2. Synthesized displacement for Case 2.




a) synthesized displacement

b) measured displacement

c) ratio of synthesized displacement and measured displacement

Figure 3. Spectra of displacement for Case 2.

wave as input, the amplitude is1.5 mm for date length 24 and 20 bits, but becomes more than 2.0 mm for 16 bits, although the exact value of the laser displacement meter is 1.5 mm.

Instead of averaging skipping is used to generate virtual data of lower sampling rate. The effects of reducing the sampling rate on time integration are similar to those shown in Fig. 2.

To see the detail of the synthesized displacement, the Fourier spectra of the measured data are shown in Fig. 3; the measured acceleration is converted to displacement for the comparison with the measured displacement. The ratio of the Fourier spectra is also plotted in Fig. 3. The ratio is almost 1 up to 5 Hz. However, it then tends to decreases to 0, with some fluctuation of the order of magnitude 1. There are even some spikes in the ratio, say, at 3.5 and 7.0 Hz, which correspond to the device noise of the prototype accelerometers.

The fluctuation of the ratio after 5 Hz is a source of the difference between the synthesized displacement and the measured displacement Increasing sampling rate from 100 Hz to 1,600 Hz does not contribute to tame the fluctuation. Contribution can be expected only for frequency components higher than 10 Hz, since a frequency component at 10 Hz is measured only10 times at the sampling rate of 100 Hz. To monitor the seismic response of a structure, however, accurately measuring these high frequency components is of secondary significance.

When a filtering scheme is used for the time integration, the errors in higher frequency components produce larger errors unless high cut filter is implemented. In the present case, simple filtering schemes produce significant errors in phases, even if base alignment is made. If the data storage allows, it is better to store all data and to apply the DFT for time integration.

## 4. TIME SYNOHRONIZATION

When acidometers are installed to a structure, it is preferable to take time synchronization. This is because synchronized data enables one to obtain i) modes of structure responses and ii) response functions at specific points. Time synchronization, however, is difficult for spatially distributed sensors. A conventional method is to send a time stump to all sensors. This method, however, results in frequent communication among them. As an alternative, the authors are studying time synchronization that is based on data analysis, even though the accuracy of synchronization is not high as the communication-based time synchronization.

### (1) Methodology of Taking Time Synchronization

When P-wave hits a structure, its vertical response has a sharp rise. Finding this rise in measured data leads to time synchronization for sensors; the vertical response of the structure is more like a rigid-body compared with the horizontal responses.

Table 2. Earthquake used for data analysis.

| ID | epicenter | data |
|---|---|---|
| 1 | Fukushimakenoki | 05/04/04 |
| 2 | Miyagikenoki | 05/08/16 |
| 3 | Fukushimakenoki | 05/10/19 |
| 4 | Fukushimakenoki | 05/10/01 |
| 5 | Iwateken | 05/11/15 |
| 6 | Miyagikenoki | 05/12/02 |
| 7 | Miyagikenoki | 05/12/05 |
| 8 | Miyagikenoki | 05/12/17 |
| 9 | Miyagikenoki | 06/01/18 |
| 10 | Miyagikenoki | 06/03/19 |
| 11 | Tokaidooki | 06/03/28 |
| 12 | Fukushimakenoki | 06/03/29 |
| 13 | Miyagikenoki | 06/04/02 |
| 14 | Fukushimakenoki | 06/04/10 |
| 15 | North Miayagiken | 06/06/06 |
| 16 | North Miayagiken | 06/09/09 |

The simplest methodology for this time synchronization is to make use of correlation of waveforms of the measured data. The formulation is simple. Data of the vertical component are denoted by $\{v_n\}$ which are standardized by using the maximum value, i.e.,

$$\bar{v}_n = v_n / V \qquad \left(V = \max\{|\, v_n \,|\}\right), \tag{1}$$

When standardized waveforms for the α-th and β-th sensors are given as $\{\bar{v}_n^{\alpha}\}$ and $\{\bar{v}_n^{\beta}\}$, the correlation for a shifted waveform of the α-th sensor with respect to the β-th sensor is defined as

$$C^{\alpha\beta}(\Delta t) = 1 - \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\bar{v}_{n+n'}^{\alpha} - \bar{v}_{n}^{\beta}\right)^2}}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\bar{v}_{n+n'}^{\alpha}\right)^2}\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\bar{v}_{n}^{\beta}\right)^2}} \qquad \left(\Delta t = n'dt\right), \tag{2}$$

where $\Delta t$ is the time shift and $N$ is the number of the waveform data. By definition, $\Delta t$ that makes $C^{\alpha\beta}$ maximized is the time shift with which the time synchronization is taken.

This methodology is not applicable to sensors with the sampling rate of 100 Hz; the time shift is per 0.01 sec and a possible error is too larger to monitor structure responses. Increasing the sampling rate leads to shorter time shift, and the rise of vertical movement is more clearly measured.

### (2) Time Synchronization at Higher Sampling Ratio

The authors have been continuously monitoring an RC building in Sendai City since 2005. Three prototypes of an acidometer which has 2,000 Hz sampling rate and 24 bit data length are installed at different floors. The data-analysis based time synchronization is examined by using data of actual structure responses measured by these three sensors.

Table 2 summarizes earthquakes at which the structure responses are observed. Figure 4 shows an example of the observed acceleration waveform of earthquake ID 1. The reference sensor is denoted by No. 1, and the correlation of the other sensors, denoted by No. 2 and 3, are calculated. As shown in Table 3, six time windows in which the correlation is computed are studied; time 0 is set at the instance of the rise.

Figure 5 presents the shifted waveforms that have the maximum correlation and the change in the correlation with respect to the time shift; the time window of No. 1 is used. It is clearly seen that the correlation takes the maximum value for the UD components. This is because the vertical structure responses are more like a rigid-body. For other time windows, the maximum value is obtained for the UD components. The time shift at which the correlation is maximized is almost the same for the time window of 1.0 and 0.8 [sec], but the time shift is slightly different for the time window of 0.6 [sec]. Including pre-rise does not reduce the correlation.

Based on the above preliminary analysis, vertical components

Table 3. Setting of time window.

| time window | initial time [sec] | final time [sec] | duration [sec] |
|---|---|---|---|
| 1 | 0.0 | 1.0 | 1.0 |
| 2 | 0.0 | 0.8 | 0.8 |
| 3 | 0.0 | 0.6 | 0.6 |
| 4 | -0.5 | 0.5 | 1.0 |
| 5 | -0.4 | 0.4 | 0.8 |
| 6 | -0.3 | 0.3 | 0.6 |

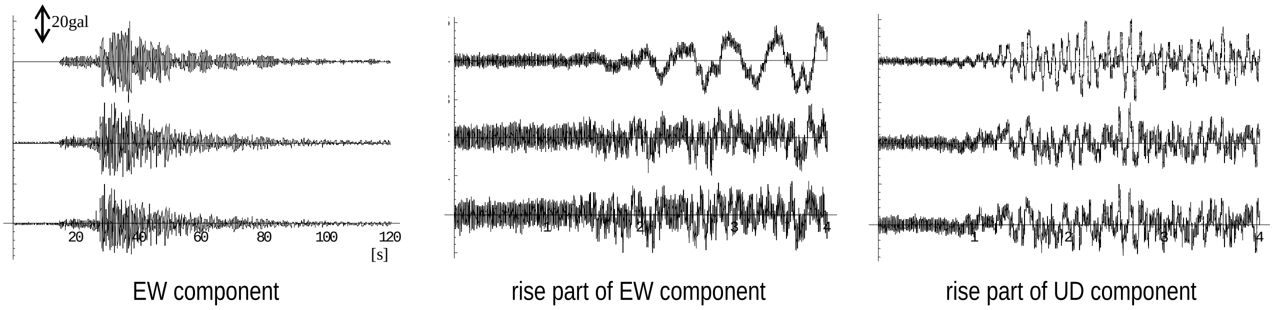



Figure 4. Example of measured acceleration waveform: earthquake ID = 1.

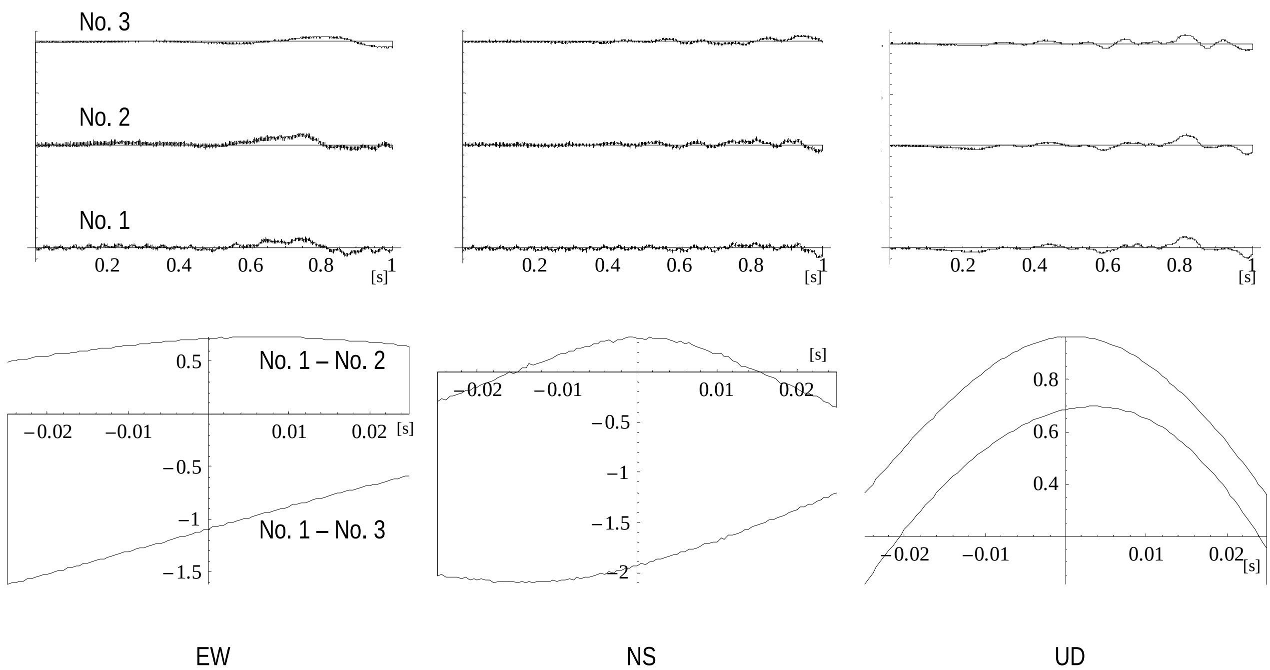



Figure 5. Synchronized rise of waveform and change in correlation for time shift: earthquake ID = 1.

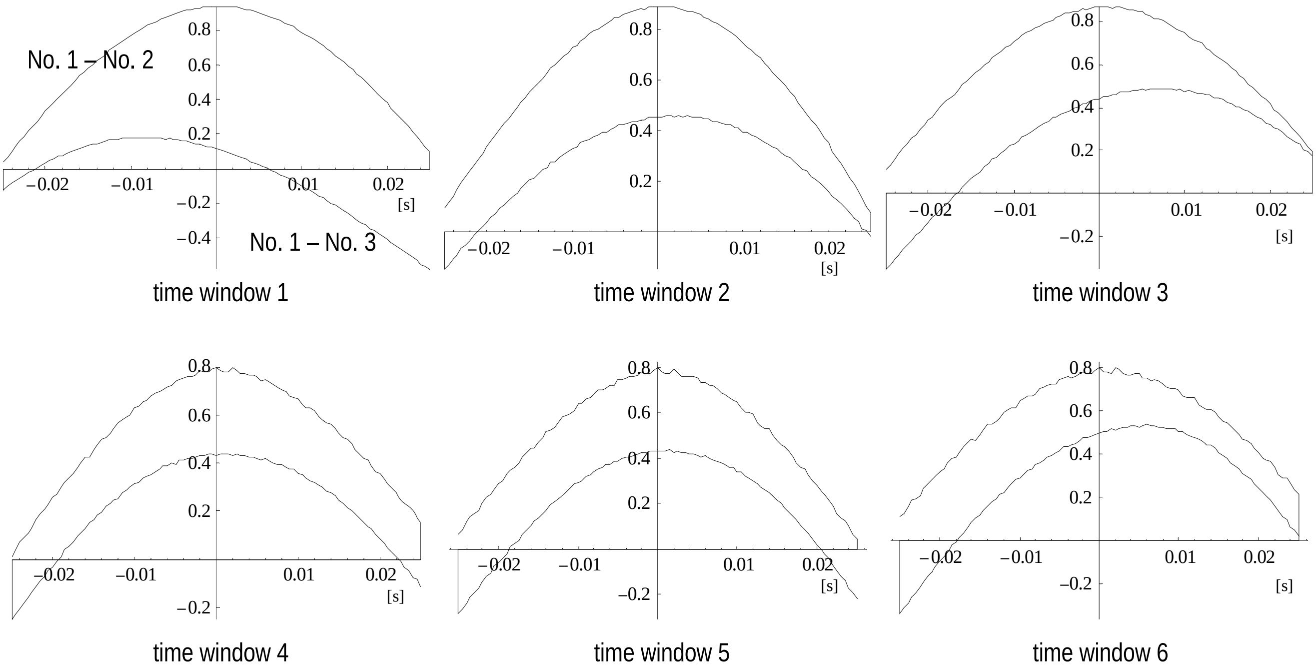



Figure 6. Change in correlation for time shift: earthquake ID = 5.

Table 4. Results of time synchronization.

| ID | time window | | | |
|---|---|---|---|---|
| | 1 | | 4 | |
| | 1-2 | 1-3 | 1-2 | 1-3 |
| 1 | s | s | s | s |
| 2 | s | s | s | s |
| 3 | s | s | s | s |
| 4 | s | s | s | s |
| 5 | s | s | s | s |
| 6 | s | s | s | s |
| 7 | s | s | s | s |
| 8 | s | s | s | s |
| 9 | s | s | s | s |
| 10 | s | s | s | s |
| 11 | f | f | f | f |
| 12 | s | s | s | s |
| 13 | s | s | s | s |
| 14 | s | s | s | s |
| 15 | s | s | s | s |
| 16 | s | s | s | s |

(s: success, f: fail)

of other data are analyzed and the results for 15 data shown in Table 2 are presented. The change in the correlation with respect to the time shift is plotted, in order to examine the most suitable time window. The points of examination are the following two: 1) the usefulness of including the pre-rise data and 2) the shortest time duration with which the time shift is accurately computed.

As a typical example, the results of analyzing earthquake ID 5 are presented in Fig. 6. It is clearly seen that the correlation takes a peak with respect to the time shift for all the six widnows. The time shift for the maximum correlation is the same for No. 1 and No. 2 sensors, although some difference is observed for the time shift for No. 1 and No. 3 sensors; the time shift is 0.00 sec for the time windows 2, 4 and 5, but the time shift is -0.08 sec or 0.08 for other time windows. Some fluctuation is observed for the correlation curve for the time windows 5 and 6.

As expected, the best performace of finding the correlation peak is achieved by the time windows 1 and 4. Table 4 summarizes success/fail of time synchronoziation when the time windows 1 and 4 are used. As is seen, except for one earthquake, the peak of the correlation is found like Fig. 6. The failure is due to the fact that the amplitude of the meauserd accelearion is small and hence its S/N ratio is low.

It seems that when the duration of a time window is longer than 0.8 sec, the correlation takes the maximum value. Some differences are found whether the pre-rise data are included or not. The value of the difference is relatively small, less than 0.01 sec for the present data. Such difference is not significant to take the time synchronization that is needed for structure seismic response analysis.

## 5. CONCLUDING REMAKRS

The following concluding remarks are drawn from the shaking table experiment and the data analysis of observed acceleration:

1) higher sampling rate contributes to more accurate time integration even though data length is a more critical element;
2) DFT should be used when high sampling acceleration data are integrated to accurately compute displacement or velocity.
3) waveforms measured at 2,000 Hz sampling rate leads to data-analysis based time synchronization with errors less than 0.01 sec.
4) time windows for the data analsysis should have duration more than 0.8 sec.

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## 時間積分と時刻同期のための加速度計の高速サンプリングについて

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加速度計のサンプリングレートを1,600ないし2,000Hzに上げることで，高度な時間積分と時刻同期が実現する可能性がある．これは，計測された加速度を時間積分することで変位・速度を高精度に計算することと，時間分解能の高い計測データを分析することで複数のセンサの時刻同期をとることである．震動台を使った実験と構造物の実データを解析することで，上記の二点に対する高速サンプリングレートの効果を検証した．この結果，高速サンプリングレートが時間積分の精度向上には相応の効果があること，複数のセンサの時刻同期を簡単に取ることができることが示された．