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[S18-3] The validation of sensor on-vehicle for evaluation of actual bridges with signal processing

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Keywords: Vehicle-Bridge Interaction(VBI), MEMS, Spatial Singular Mode Angle(SSMA), Drive-by bridge inspections

Bridge is unique because its environment and background are diverse. The uniqueness of each bridge makes its inspection difficult. In Japan, which has many old bridges, periodic inspections are mandatory, while the efficiency of visual check is low. To improve the efficiency, sensor-based inspections should be adopted. However, the direct installation of sensors on the bridges to detect their damages is still quite costly. To reduce the total cost of bridge maintenance, screening. For example, change of natural frequency is depended to rigidity of bridge, thus the detection of small damage needs extreme accurate and robust sensors if before the rigidity change becomes larger. A lot of sensors are necessary for modal analysis, and the robustness to numerical integration is required for calculation of accurate deflection. They cause the growth of total cost for bridge maintenance, and it can be assumed that the feasibility will become lower. Additionally, it is considered that the power supply and communication system are necessary for realization of long term bridge monitoring. This study focuses on vibration of vehicle going on the bridge. Since it is difficult to estimate accurate bridge vibration from vehicle vibration because the vehicle-bridge interaction is complex dynamics problem, the technology is applied as a screening technique. Screening technique can optimize the resource (e.g.: human and sensor) for inspection, evaluation and repair by carrying out of the triage of bridges which have to be inspected in detail. The vehicle sensor is designed based on a common concept considering in future installation on bridges. Due to detect the effects of structural changes, it is necessary that the quantum resolution of the Analog-Digital converter (ADC) is high. Previous study uses about 16 bits commonly, thus this study developed several acceleration sensor devices which mount an ADC of 18 to 24 bits and experimented on several actual bridges. Sensors were installed on both the vehicle and the bridge, and the vibrations of both sensors were compared and evaluated. The criterion for identification uses Spatial Singular Mode Angle (SSMA) which assumes bridge vibration from interpolated vehicle ones by singular values decomposition. SSMA has been proved as damage detection criterion for bridge through previous study. Although it is difficult for vehicle sensors to completely reproduce bridge vibrations, it was suggested that statistical analysis of SSMA etc… may capture structural change of actual bridges.

The validation of sensor on-vehicle for evaluation of actual bridges with signal processing

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ABSTRACT

Bridge has a diversity. Various environments and backgrounds create a uniqueness of the bridge, making inspection and evaluation difficult. In Japan, the number of bridges 50 years after construction has been increasing, on the other hands, regular inspections have become mandatory, however the efficiency was not high because of visual inspection. This study focuses on vibration of vehicle going on the bridge. Since it is difficult to estimate accurate bridge vibration from vehicle vibration because the vehicle-bridge interaction is complex dynamics problem, the technology is applied as a screening technique. Screening technique can optimize the resource (e.g.: human and sensor) for inspection, evaluation and repair by carrying out of the triage of bridges which have to be inspected in detail. The vehicle sensor is designed based on a common concept considering in future installation on bridges. Due to detect the effects of structural changes, it is necessary that the quantization bit rate of the Analog-Digital converter (ADC) is high. Previous study uses 12 t16 bits commonly, thus this study developed several acceleration sensor devices which mount an ADC of 17 and 23 bits and experimented on actual bridge. Sensors were installed on both the vehicle and the bridge, and the vibrations of both sensors were compared and evaluated. The criterion for identification uses Spatial Singular Mode Angle (SSMA) which assumes bridge vibration from interpolated vehicle ones by singular values decomposition. SSMA has been proved as damage detection criterion for bridge through previous study. Although it is difficult for vehicle sensors to completely reproduce bridge vibrations, it was suggested that statistical analysis of SSMA etc... may capture structural change of actual bridge.

Keywords: Vehicle-Bridge Interaction, Vehicle Response Analysis, Spatial Singular Mode Angle, Bitrate of AD Converter

1. INTRODUCTION

Recent years in Japan, inspections only which can perform as same as visual inspection have been accepted legally, for instance sensor or UAV. Inspections by sensors have the capacity to directly capture structural changes. However, installation of sensor on the bridge directly is hard, and the cost for detection of the slight influence from structural changes becomes often high. For example, change of natural frequency is depended to rigidity of bridge, thus the detection of small damage need extreme accurate and robust sensors if before the rigidity change becomes larger. A lot of sensors is necessary for modal analysis, and the robustness to numerical integration is required for calculation of accurate deflection. They causes the growth of total cost for bridge maintenance, and it can be assumed that the feasibility will become lower. Additionally, it is consider that the power supply and communication system are necessary for realization of long term bridge monitoring.

Putting sensor on bridge often does it only becomes cost labor, but also power supply problem is occurred. Ones on vehicle doesn't become expensive, and not measure accurately. The spec of sensor on vehicle and the index based on the measure data should be validate considering this problem. Yan et al proposed the method to estimate the bridge natural frequency from vehicle vibration with solved the Vehicle-Bridge Interaction (VBI), however, their study didn't consider the road profile [1]. Nagayama et al estimated the natural frequency of bridge with considered the road profile [2]. The bridge natural frequency can't be estimated easily because the effect of damage is small and they is disturbed by measurement noise, thus the cost of sensor becomes high to capture them. On the other hands, the method using mode shape for damage detection is proposed [3-5]. SSMA, which is one of the damage index for bridge damage based on estimated mode shape, use the Singular Value Decomposition (SVD), hence the mode is expected to be robust for time space. Continuous SSMA is proposed to detect the structural change [6]. This index is calculated from continuous vehicle vibration data, with shift of a fixed calculation length. However, the amplitude of bridge response is smaller than the vehicle one, the estimated mode shape is often affected from quantization bit rate of analog-digital converter (ADC). This study evaluates the effect to frequency or SSMA from the difference in bitrate of ADC. The vehicle put on two sensor systems which has 17 or 23 bit resolution is used for measurement experiment on three actual bridge, and the frequency analysis and calculation SSMA based on the data measured by both of

sensor systems. The effect of ADC bitrate to mechanical index for bridge screening technology based on signal processing such as frequency or SSMA. SSMA is validated based on bridge length which is structure characteristic and vehicle velocity.

2. VEHICLE-BRIDGE INTERACTION THEOREM

2.1. Vehicle model and Spatial Singular Mode Angle

The mathematical theorem of SSMA is shown. Calculation needs vibration and position at the front, rear axles of vehicle. The vibration should be obtained from mass points under the spring. The assumed vehicle (Half Car) model is shown in Figure 1. This model has a rigid body as sprung-mass system, of which mass is m_s, and of which inertia moment is I_s. The point G indicates the centre of gravity, and the distances from the point G to the front and the rear axles are L_1 and L_2, respectively. In this figure, it is noted that L_1 and L_2 described as if as equal, however they are ordinary different because the engine often put near front wheel. The subscript i (= 1, 2) represents the front and rear axles. $z_{si}(t)$ and $z_{ui}(t)$ are the vertical displacements of the sprung-mass and the unsprung-mass. $u_i(t)$ is the forced displacement input under the i-th axle. k_{si} and c_{si} are the spring stiffness and the damping of the spring-mass at the i-th axle. m_{ui}, k_{ui} and c_{ui} are the mass, spring stiffness and damping of the unsprung-mass at the i-th axles, respectively. The equation of motion of the vehicle can be described by the following.

$$\mathbf{M}_V \ddot{z}(t) + \mathbf{C}_V \dot{z}(t) + \mathbf{K}_V z(t) = \mathbf{C}_P \dot{u}(t) + \mathbf{K}_P u(t) \tag{1}$$

where

$$z(t) = \begin{Bmatrix} z_{s1}(t) \\ z_{s2}(t) \\ z_{u1}(t) \\ z_{u2}(t) \end{Bmatrix} \tag{2}$$

$$u(t) = \begin{Bmatrix} u_1(t) \\ u_2(t) \end{Bmatrix} \tag{3}$$

$$\mathbf{M}_V = \begin{bmatrix} \dfrac{L_2 m_s}{L_1 + L_2} & \dfrac{L_1 m_s}{L_1 + L_2} & & \\ \dfrac{I_s}{L_1 + L_2} & -\dfrac{I_s}{L_1 + L_2} & & \\ & & m_{u1} & \\ & & & m_{u2} \end{bmatrix} \tag{4}$$

$$\mathbf{C}_V = \begin{bmatrix} c_{s1} & c_{s2} & -c_{s1} & -c_{s2} \\ L_1 c_{s1} & -L_2 c_{s2} & -L_1 c_{s1} & L_2 c_{s2} \\ -c_{s1} & 0 & c_{s1} + c_{u1} & 0 \\ 0 & -c_{s2} & 0 & c_{s2} + c_{u2} \end{bmatrix} \tag{5}$$

$$\mathbf{K}_V = \begin{bmatrix} k_{s1} & k_{s2} & -k_{s1} & -k_{s2} \\ L_1 k_{s1} & -L_2 k_{s2} & -L_1 k_{s1} & L_2 k_{s2} \\ -k_{s1} & 0 & k_{s1} + k_{u1} & 0 \\ 0 & -k_{s2} & 0 & k_{s2} + k_{u2} \end{bmatrix} \tag{6}$$

$$\mathbf{C}_P = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ c_{u1} & 0 \\ 0 & c_{u2} \end{bmatrix} \tag{7}$$

$$\mathbf{K}_P = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ k_{u1} & 0 \\ 0 & k_{u2} \end{bmatrix} \tag{8}$$

respectively. ($\dot{\ }$) and ($\ddot{\ }$) denote the first-order and second-order time differentiation.
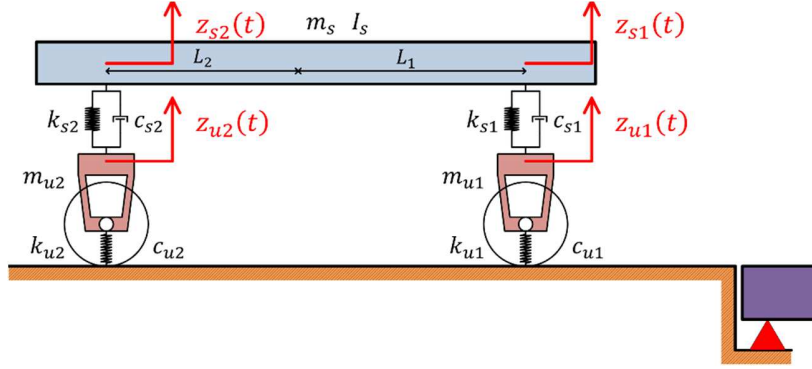

Figure 1. Vehicle (Half Car) Model.

Since the number of sensors are same with that of estimated mode shapes, when we set a sensor on each axle, only the first and second modes can be obtained. When we use only lower mode shapes, their variation can be explained only from two factors: the measurement environment and the structural change. The latter is, in other word, a damage. On the other hand, when we use more sensors, the main factor of variation becomes the ill condition problem, which means that the results depend only on noise, not on the status of the structure.

On the other hand, the bridge displacement at position x and time t can be decomposed as follows:

$$y(x,t) = \sum_k \phi_k(x) q_k(t) \tag{9}$$

$\phi_k(x)$ is the k-th order mode shape, and $q_k(t)$ is the k-th order basis coordinates. Substituting each axle position $x_i(t)$ into Equation 9, the bridge displacement just under the i-th axle is shown below:

$$y_i(t) = \sum_k \phi_k\big(x_i(t)\big) q_k(t) \tag{10}$$

Assuming that the road roughness at the position of x is $R(x)$, the input component of the i-th axle of the vehicle at the time of t is shown below:

$$r_i(t) = R\big(x_i(t)\big) \tag{11}$$

Then, the forced displacement inputs can be described by

$$\boldsymbol{u}(t) = \boldsymbol{y}(t) + \boldsymbol{r}(t) \tag{12}$$

where

$$\boldsymbol{y}(t) = \begin{Bmatrix} y_1(t) \\ y_2(t) \end{Bmatrix} \tag{13}$$

$$\boldsymbol{r}(t) = \begin{Bmatrix} r_1(t) \\ r_2(t) \end{Bmatrix} \tag{14}$$

On the other hand, assuming that

$$\boldsymbol{\Phi}(t) = \begin{bmatrix} \phi_1\big(x_1(t)\big) & \phi_2\big(x_1(t)\big) \\ \phi_1\big(x_2(t)\big) & \phi_2\big(x_2(t)\big) \end{bmatrix} \tag{15}$$

$$\boldsymbol{q}(t) = \begin{Bmatrix} q_1(t) \\ q_2(t) \end{Bmatrix} \tag{16}$$

Equation 12 can be rewritten in

$$\boldsymbol{u}(t) = \boldsymbol{\Phi}(t)\boldsymbol{q}(t) + \boldsymbol{r}(t) \tag{17}$$

Next, $\phi_k\big(x_i(t)\big)$ can be discretized by interpolation as below:

$$\phi_k(x) = \sum_{j=1}^{n} a_{jk} N_j(x) \tag{18}$$

When the base function $N_j(x)$ is the Lagrangian function, the coefficient a_{kj} indicates the amplitude of k-th order mode shape at the discretized position x_j. Figure 2 shows the concept of this interpolation.
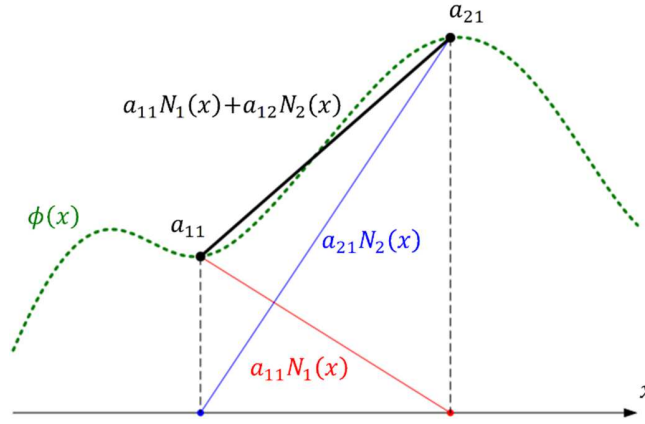

Figure 2. Concept of interpolation.

When $n = 2$ and $x_1 = L/3$ and $x_2 = 2L/3$, the Lagrangian function is

$$\begin{aligned} N_1(x) &= -\frac{3}{L}x + 2 \\ N_2(x) &= \frac{3}{L}x - 1 \end{aligned} \tag{19}$$

$$\begin{bmatrix} \phi_1\big(x_1(t)\big) & \phi_2\big(x_1(t)\big) \\ \phi_1\big(x_2(t)\big) & \phi_2\big(x_2(t)\big) \end{bmatrix} = \begin{bmatrix} N_1\big(x_1(t)\big) & N_2\big(x_1(t)\big) \\ N_1\big(x_2(t)\big) & N_2\big(x_2(t)\big) \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{20}$$

By using Equation 19 and Equation 20, Equation 18 becomes

$$\boldsymbol{\Phi}(t) = \mathbf{N}(t)\mathbf{A} \tag{21}$$

where the (k, j) component of the matrix $\mathbf{A}$ is a_{kj}. Assuming that the unsprung-mass parameters of the front and rear axles are same, which means that $k_{u1}/m_{u1} = k_{u2}/m_{u2} = k_u/m_u$ and $c_{u1}/m_{u1} = c_{u2}/m_{u2} = c_u/m_u$, the vertical acceleration vibrations of the unsprung-mass can be described by

$$\ddot{\boldsymbol{z}}_u(t) = \begin{Bmatrix} \ddot{z}_{u1}(t) \\ \ddot{z}_{u2}(t) \end{Bmatrix} = \mathbf{N}(t)\mathbf{A}\boldsymbol{\sigma}(t) + \bar{\boldsymbol{\epsilon}}(t) \tag{22}$$

where

$$\boldsymbol{\sigma}(t) = \frac{k_u}{m_u}\boldsymbol{q}(t) + \frac{c_u}{m_u}\dot{\boldsymbol{q}}(t) \tag{23}$$

$$\bar{\epsilon}(t) = -\frac{1}{m_u} \begin{bmatrix} -c_{s1} & c_{s1} + c_u \\ & -c_{s2} & c_{s2} + c_u \end{bmatrix} z(t)$$

$$-\frac{1}{m_u} \begin{bmatrix} -k_{s1} & k_{s1} + k_u \\ & -k_{s2} & k_{s2} + k_u \end{bmatrix} \dot{z}(t) \tag{24}$$

$$+\frac{k_u}{m_u} r(t) + \frac{c_u}{m_u} \dot{r}(t)$$

If the position of each axle $x_j(t)$ are available, the interpolation matrix $\mathbf{N}(t)$ can be calculated. Since the unsprung-mass vibrations $\ddot{z}_u(t)$ and the interpolation matrix $\mathbf{N}(t)$ are known, we obtain

$$\mathbf{N}^{-1}(t)\ddot{z}_u(t) = \mathbf{A}\sigma(t) + \epsilon(t) \tag{25}$$

$$\epsilon(t) = \mathbf{N}^{-1}(t)\bar{\epsilon}(t) \tag{26}$$

The left side of Equation 25 is the spatial correction of vehicle vibrations. Based on Equation 25, the mode shape $\mathbf{A}$ can be estimated by SVD (Singular Value Decomposition) of $\mathbf{N}^{-1}(t)\ddot{z}_u(t)$. By SVD, the mode shape $\mathbf{A}$ and the bridge vibration component $\sigma(t)$ are calculated at the same time. The bridge components includes only information about the bridge vibration and unsprung-mass characteristics of the vehicle. Others are included in the error term $\epsilon(t)$: the vehicle responses: $z(t)$, $\dot{z}(t)$ and the road roughness: $r(t)$ and $\dot{r}(t)$. Since $\mathbf{N}^{-1}(t)\ddot{z}_u(t)$ is time function, it can be described as data matrix $\mathbf{D} \in R^{2 \times T}$. T means the number of the measured data. The SVD of $\mathbf{D}$ is described by the product of an orthogonal matrix $\mathbf{U} \in R^{2 \times 2}$, a diagonal matrix $\mathbf{\Sigma} \in R^{2 \times 2}$ and an orthogonal matrix $\mathbf{V} \in R^{T \times 2}$ ($\mathbf{V}^{\mathrm{T}}\mathbf{V} = \mathbf{I}$: the unit matrix) as below:

$$\mathbf{D} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^{\mathrm{T}} \tag{27}$$

where $\mathbf{U}$ is the estimation of $\mathbf{A}$, and $\mathbf{\Sigma}\mathbf{V}^{\mathrm{T}}$ is the estimation of $\sigma(t)$ in the form of data matrix. In order for SVD of $\mathbf{D}$ to accurately estimate the bridge mode shape $\mathbf{A}$, the following conditions need to be satisfied:

a) $\sigma(t)$ is uncorrelated.
b) Error term $\epsilon(t)$ is white noise.

The bridge vibration components $q(t)$ and $\dot{q}(t)$ are transient responses induced by the traffic loads, in this case. Thus, it is considered that the real values of $\sigma(t)$ does not satisfy the condition of a). While the SVD process gives the estimated bridge vibration components $\mathbf{\Sigma}\mathbf{V}^{\mathrm{T}}$, they are just uncorrelated signals near $\sigma(t)$. The error due to this affects on the estimated mode shape $\mathbf{U}$. This means that the estimation mode shape $\mathbf{U}$ and the succeeding index SSMA deviate slightly from the correct mode shape. This effect on SSMA, however, can be expected to be unchanging under the same measurement condition.

Generally, a local damage on a bridge never influence the dynamic indices of the global system of the structure. Thus, it is expected that $\mathbf{A}$ remains unchanged even after the damage. However, because the local bridge responses are easily affected by the damage, the component $\sigma(t)$ changes. The estimation for it is $\mathbf{\Sigma}\mathbf{V}^{\mathrm{T}}$ and it cannot trace the transition. This error is included in the error of $\mathbf{U}$. This is the mechanism of SSMA to react a bridge's local damage.

The error term $\epsilon(t)$ does not include the bridge vibrations, but the vehicle vibrations $z(t)$, $\dot{z}(t)$ and the road profile $r(t)$, $\dot{r}(t)$. Because the influence of the damage on the bridge vibrations is a kind of pulse, the impact of the damage on the bridge vibration is not transmitted strongly to the vehicle. The error term may affect the result, but the effect is constant and can be ignored. It is noted that the property, which affects SSMA, is the running speed of the vehicle, because the conversion process in Equation 11 depends on time space.

From the above consideration, although $\mathbf{U}$, the estimated bridge mode shape in Equation 27, is different from the actual value $\mathbf{A}$, it can be used as an evaluation index for the bridge health. It also suggests that SSMA is a possible indicator for bridge screening, because it is more sensitive than the actual mode shape.

3. EXPERIMENT ON ACTUAL BRIDGE

Experiment is carried out on PC and Steel bridges. They are two PC and one steel and called as PC1, PC2 and S1. Acceleration and their power spectrum (PS) on 17 and 23 bit rate are shown in Figure. 3. The vehicle vibration over bridge is identified from GPS position of sensor on vehicle and bridges entrance and exit. Blue shows the front unsprung z axis vibration, and orange shows the rear one. Gravity direction is negative. SSMA uses the unsprung vibration, thus this study focuses them. The bridges and vehicle parameter are shown in Table. 1. The velocity of vehicle is decided by actual traffic speed. Other vehicles which go through the same bridge then is ignored because the experiment vehicle weight is very heavy (13.8t) and it is confirmed that the similar weight vehicle didn't go with the experiment vehicle when the data in this study are measured. All bridges are evaluated as level I by Japanese bridge inspection expert. The sensor position on vehicle is shown in Figure. 4.

Acceleration amplitude is different with 17 and 23 bit ADC, because they can be affected from the position or eccentricity.
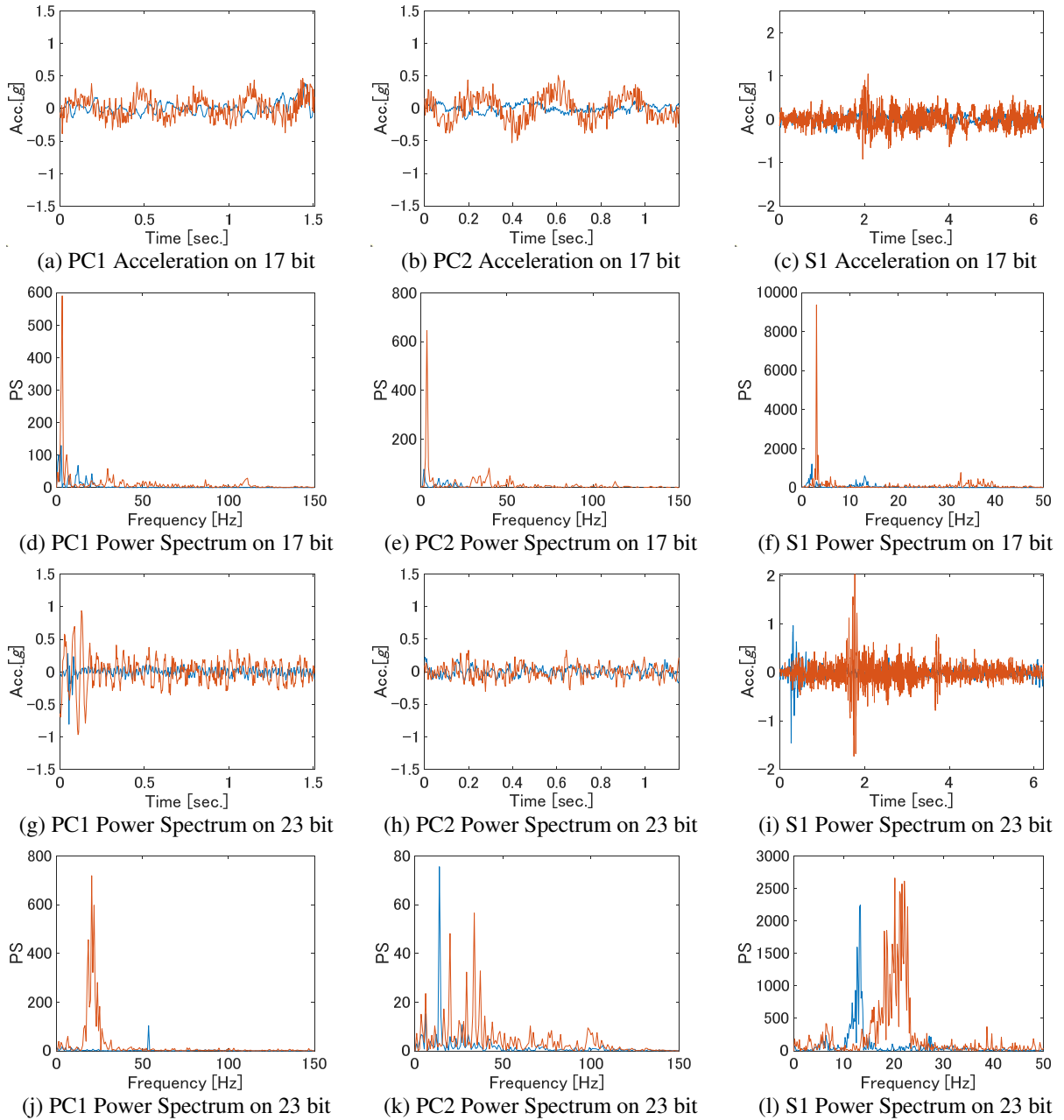

(a) PC1 Acceleration on 17 bit   (b) PC2 Acceleration on 17 bit   (c) S1 Acceleration on 17 bit

(d) PC1 Power Spectrum on 17 bit   (e) PC2 Power Spectrum on 17 bit   (f) S1 Power Spectrum on 17 bit

(g) PC1 Power Spectrum on 23 bit   (h) PC2 Power Spectrum on 23 bit   (i) S1 Power Spectrum on 23 bit

(j) PC1 Power Spectrum on 23 bit   (k) PC2 Power Spectrum on 23 bit   (l) S1 Power Spectrum on 23 bit

Figure 3. Acceleration and Power Spectrum on experiment bridges (17 and 23 bit ADC).

The PS of 17bit has peaks on low frequency (~10Hz). The shorter bridge often has around 10 Hz as natural frequency, thus the result is proper. Notice the short PC bridge are ordinary more rigid than similar steel ones.

On the other hands, the acceleration of 23 bit ADC captures the peaks which is seems to have been when going over joint. The PS on high bitrate has more peaks on higher frequency although there are small peaks in lower 10 Hz. This result can be caused by high bitrate noise because the higher bitrate ADC is more affected from electrical or heat disturbance. However, notice the SSMA is robust for high time frequency noise because it calculated from the assumed bridge vibration by Singular Value Decomposition (SVD) which can decompose the signal to time or spatial frequency domain.

4. ANALYSIS AND DISCUSSION

The SSMA is the index for capture of structural change. However, previous study shows that the calculation is affected from vehicle velocity [6]. Therefore, it is desirable that SSMA should be robust for velocity change and sensitive for structural change. SSMA calculated from experiment result plot with vehicle velocity or span length for horizontal axis. The velocity – SSMA 2D plot are shown in Figure. 5, and the length – SSMA 2D plot are shown in Figure. 6. Blue crosses are the SSMA on low (17 bit) bitrate, and the red ones are high (23 bit) bitrate. In this study, the length change is assumed as most dominant structural change.

The variance of velocity is 126. The variance of SSMA on 17 bit is 123.5 and the variance on 23 bit result is 7.22. The variance of SSMA with velocity change is desirable to be small because previous study [6] suggests bridge damage makes the variance of SSMA greater. The SSMA on 17 bit is changed with velocity and the change seems to be independent on the length change. The change on 23 bit with velocity is smaller than result in 17 bit, and it seems to depend on length change than the result in 17 bit. Since SSMA should behavior along with structural change rerated to bridge mode, this suggest the result on 23 bit is preferable. The trends of ADC (i.e. low frequency components) which can affect to mode angle estimation is generated from the accumulation of quantization error, and the error becomes more greater by the calculation length change with velocity change when the bitrate is lower. Therefore, this result suggests that the index using vehicle vibration on VBI such as SSMA can require the high bitrate ADC.

Table 1. The parameter in Experiment

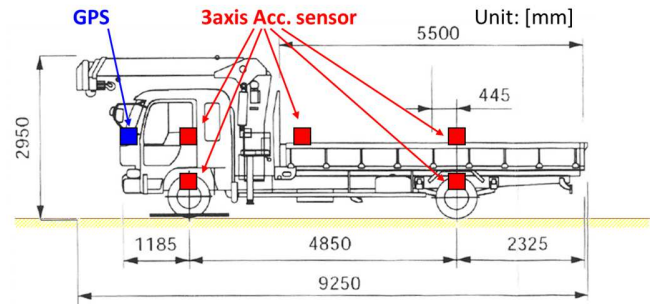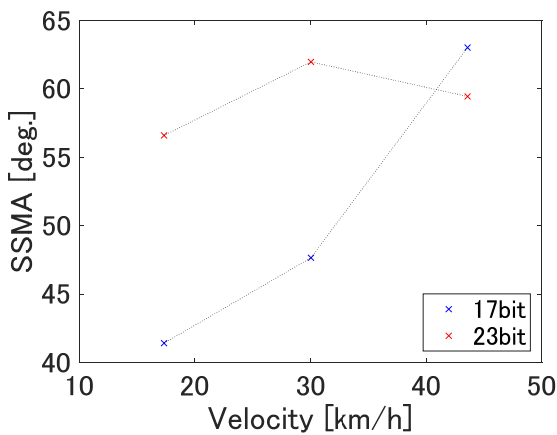|	PC1	PC2	S1
Span [m]	12.6	14	30
Girder Type, Number	I	T, 4	Steel, 4
Vehicle Weight [t]		13.8	
Vehicle Velocity [km/h]	17.3	43.6	30.0

Figure 4. The position of sensor on vehicle

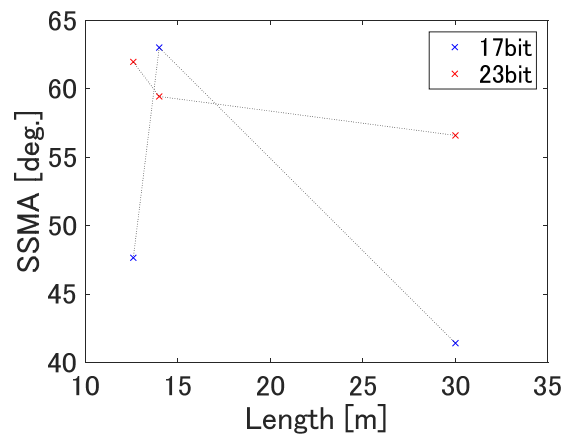*Figure 5. Vehicle velocity - SSMA*

Figure 6. Span length - SSMA

5. CONCLUSIONS

This study validates that the difference of Analog Digital Converter bitrate affect the performance of the bridge damage index such as natural frequency or Spatial Singular Mode Angle by comparison of the result in three actual bridges experiment. The findings is shown as below:

1. For validation of the effect of ADC bitrate to the bridge damage index, two bitrate (17 and 23 bit for low and high) ADC is prepared for experiment on actual bridges. The measured acceleration amplitudes are different because the position or eccentricity, however, peaks which are considered as the bridges natural frequency is appear.

2. Lower bitrate acceleration and their power spectrum is seems to have a strong low frequency component. This can be caused by the calculation length change expanded the effect of quantization error when the bitrate is lower.

3. Higher bitrate and their power spectrum has a strong high frequency component which may be generated from the electrical and heat disturbance. However, SSMA which can expect as a robust index to high time frequency noise are also robust to the vehicle velocity change. On the other hands, the change with length change which was assumed as the most dominant structural change in this study reacts more linearly than the lower bitrate result.

In this experiment, the vehicle running was repeated and the data could be obtained on the other bridge. For future works, the validity of this study analysis is verified through the statistical analysis. In addition, the feasibility of the screening (in the future, inspection) using SSMA will be verified in the field experiment at large area.

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