FUNDAMENTAL DISCUSSIONS FOR PRACTICAL APPLICATION OF HEALTH MONITORING SYSTEM FOR SHORT- AND MEDIUM-SPAN BRIDGES BASED ON PUBLIC BUS VIBRATION

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ABSTRACT: In our country, the aged bridges are increasing when it were constructed at the rapid economic growth. Therefore, we investigate aged bridges regularly, and it is desirable to detect early detection. Thus, we are developing the health monitoring system for short- and medium span bridges to detect performance deterioration, which is installed an acceleration sensor under the rear wheel spring of the bus.

Firstly, let us examine fundamental discussions for practical application of health monitoring system.

Next, the index to detect performance deterioration of bridges is characteristic deflection which is defined based on the vibration data from the sensor originally. With the characteristic deflection property value, it is demanded from the vibration data of the acceleration sensor by averaging a deflection. However, it is not found clearly that influence of the characteristic deflection property value on environmental monitoring which is the location of sensor, velocity of the car, season (temperature) and weight of the vehicle.

In this study, it takes consideration of influence of the characteristic deflection property value on environmental parameters using by an aged bridge. As a result, our practical experiment makes it clear that it influence of this value.

KEYWORDS： Public bus, SHM, vibration, field test, influence of characteristic deflection

1. INTRODUCTION

In our country, the aged bridges (about 670,000) are increasing when it were constructed at the rapid economic growth (1955 through 1973). The number of the bridges reaching 50 years will reach approximately 3 times after 10 years later, approximately 7 times after 20 years later in future[1]. In order to reconstruct all bridges, it needs to spend a huge cost and expense. Therefore, the bridges are periodically inspected, and condition of damaged bridges is discovered early.

The progress of deterioration progress due to safety level is shown in Figure1. It is thought that a sudden change of bridge's conditions grows big from accumulation damage probability by the relations of the secular changed as for the structure in the early stage of the deterioration period from last part of the acceleration period when an injured structure is not maintained. Therefore, during an interregnum of the inspection, the structural fatal injury is missing. As a result, serious problems are caused in management.

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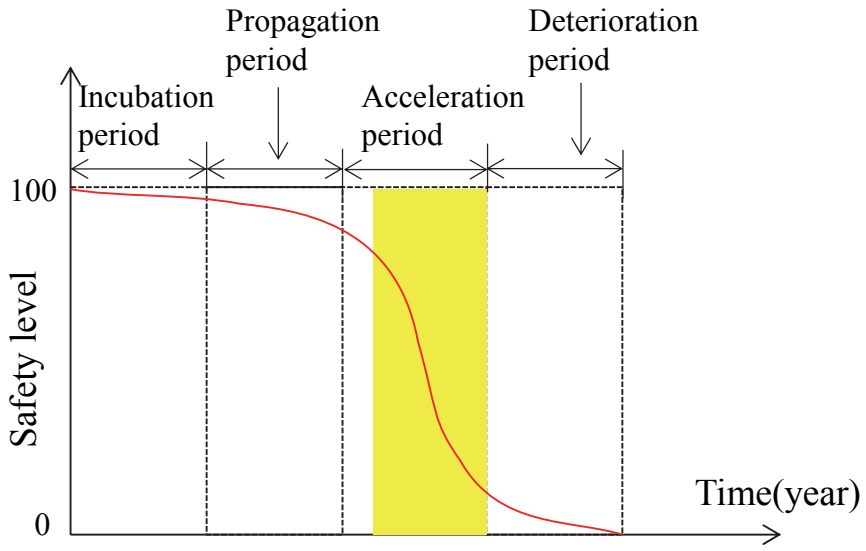

Figure 1. Progress of deterioration progress due to safety level

Therefore, interval of time of inspection will be shortened, these problems are evaded. However, it is difficult from a budget and a problem such as the lack of engineer practically. For that reason, it is necessary to make a system which supplements the periodic inspection. Regular monitoring using SHM (Structural Health Monitoring) which installs a direct sensor in the bridge for one means is effective. But, there are many problems that must be settled to introduce it. It is difficult to meet economical rationality, and to realize the regular monitoring for the long term using by SHM or visual inspection for huge amount of aged bridges.

In this study, we are developing the health monitoring system for short- and medium span bridges to detect performance deterioration, which is installed an acceleration sensor under the rear wheel spring of the bus [2-3]. In order to evaluate bridges, property of the characteristic deflection value is demanded from the vibration data of the acceleration sensor by averaging a deflection. We are investigating influence of the characteristic deflection property value on environmental monitoring which is the location of sensor, velocity of the car, season (temperature) and weight of the vehicle.

2. THE BASIC THEORY IN BRIDGE MONITORING SYSTEME USING BY PUBLIC BUS

2.1 Outline of our SHM system

In this SHM system [4] is using fixed-route bus for public transportation. This method means that judging of the safety performance due to the structural damage based on “characteristic deflection” which doesn’t influence dynamic agitation due to road surface irregularity. Outline of monitoring procedure of SHM using fixed-route bus is shown in Figure2.

First, fixed-route bus installed accelerometer is measured the target bridge. Second, it calculates the characteristics deflection using by collecting the vertical accelerometer. These data are needed 15 times. If our SHM system is already 15timese measured, mean value with the “characteristic deflection” is calculated at the 15 times. Next, average of the “characteristic deflection” in times series are observed. Next, our SHM system is checked that the “characteristic deflection” reaches or not the threshold which is of calculated by analysis. These processes are kept until “characteristic deflection” exceeded the threshold. Finally, if the “characteristic deflection” is exceeded the threshold, it needs to maintain the bridge such as inspection.

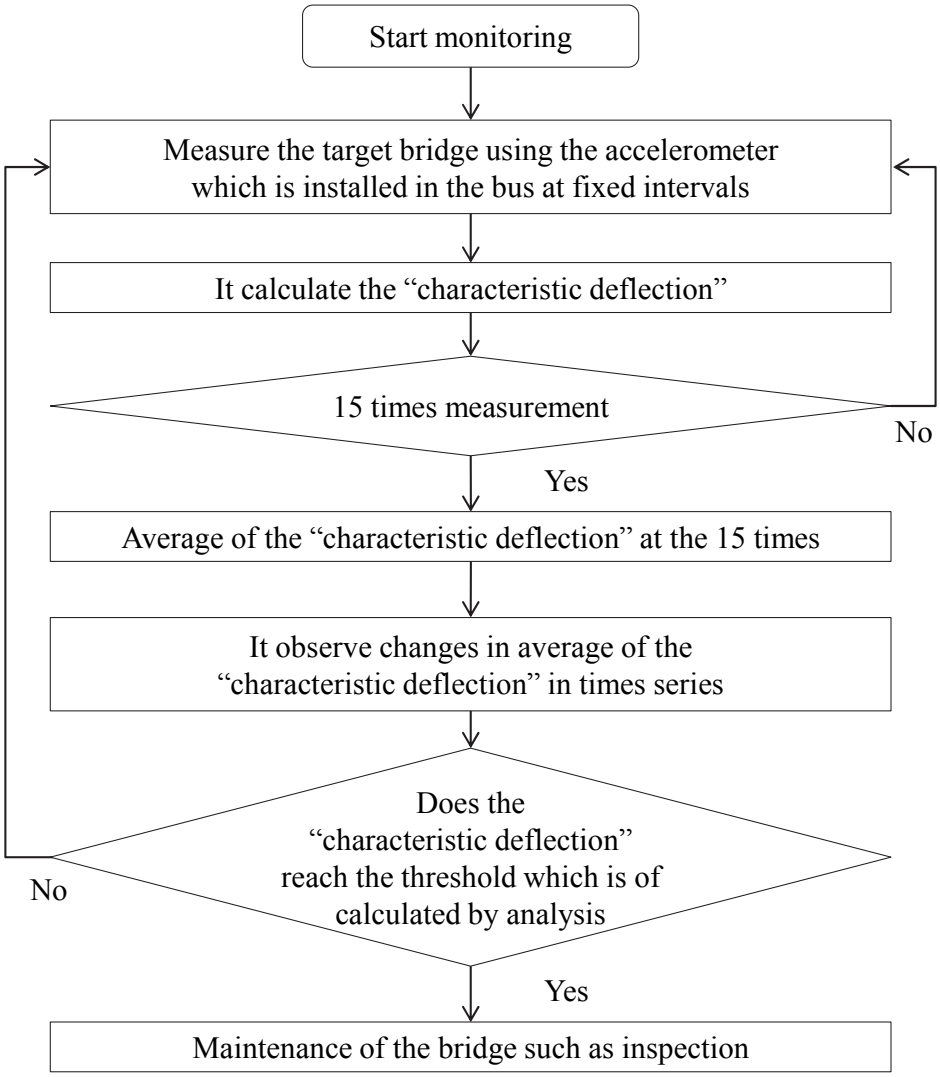

Figure 2. Flow of the monitoring of bridge conditions using public bus

2.2 Method of the “characteristic deflection”

The flowchart of calculating “characteristic deflection” is shown in Figure3.

Step1. Trimming of the acceleration data

The data of the vertical accelerometer is trimmed when passed the bridges using recording the time in the bus as reference in Figure4.

Step2. Estimation of time when passed the center of span

It is estimated time when passed the center of span based on passed the expansion joint. Because of part of expansion joint, it is vibrated the biggest when passed the bridge. Thus, it is estimated time of passed expansion joint based on the biggest acceleration from measurement data. The variable of the acceleration is different depend on service conditions, it is focused on the Figure5 of the estimate bend to be provided by integrating 2 times of acceleration data of the vertical direction. As shown in Figure5, it is clearly to find the feature wave, when passed the expansion joint. Therefore, several times of acceleration from field data are synchronized based on a characteristic wave pattern, and then the wave of center of span is estimated.

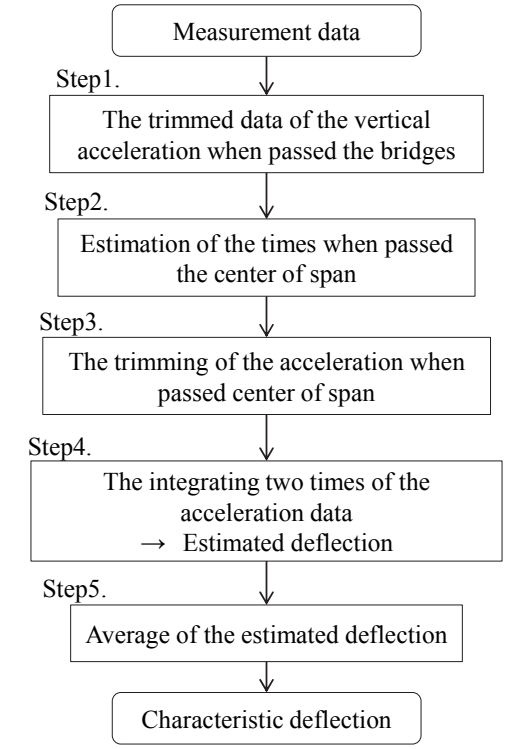

Figure 3. Flow of the calculating "characteristic deflection"

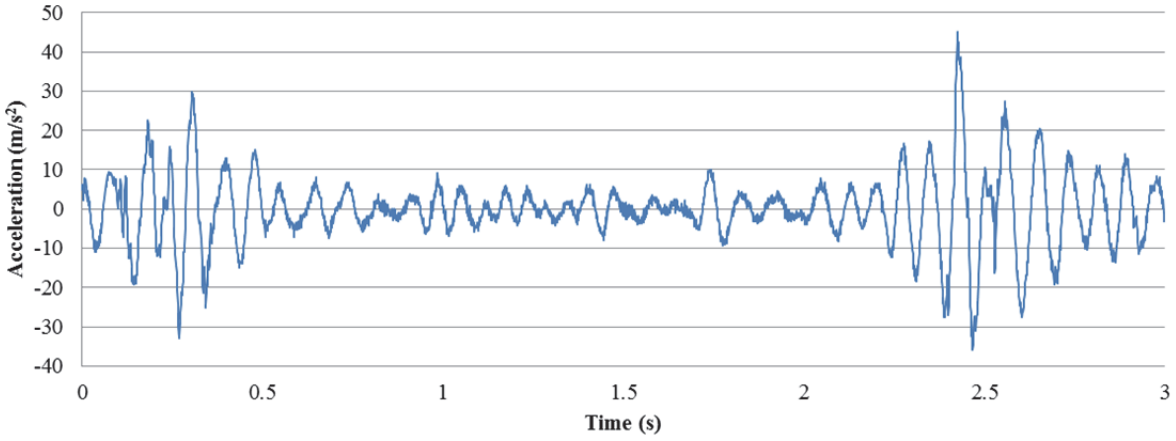

Figure 4. Vertical acceleration when passed bridge

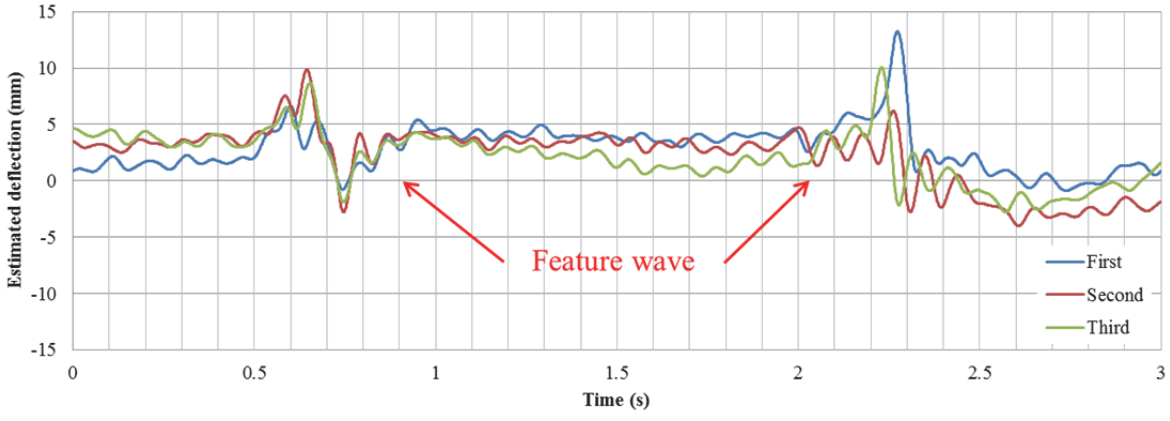

Figure 5. Feature wave of estimation deflection

Step3. The trimming of the acceleration when passed center of span

The acceleration data as shown in Figure6 is trimming using by estimation time (Step2) when passed the center of span.

Step4. The integrating two times of acceleration data

In this step, it is calculated displacement by integrating two times of acceleration data which is trimmed. We call the estimated deflection as shown in Figure7. In detail, as shown in Figure8 acceleration data are converted into the velocity, and an approximate quadratic curve is calculated. The converted velocity is made errors using an approximate quadratic curve. Then the errors corrective velocities are converted into the deflection. This value is estimated deflection.

Step5. The calculating characteristic deflection

The characteristic deflection is calculated by average of the estimated deflection on time series.

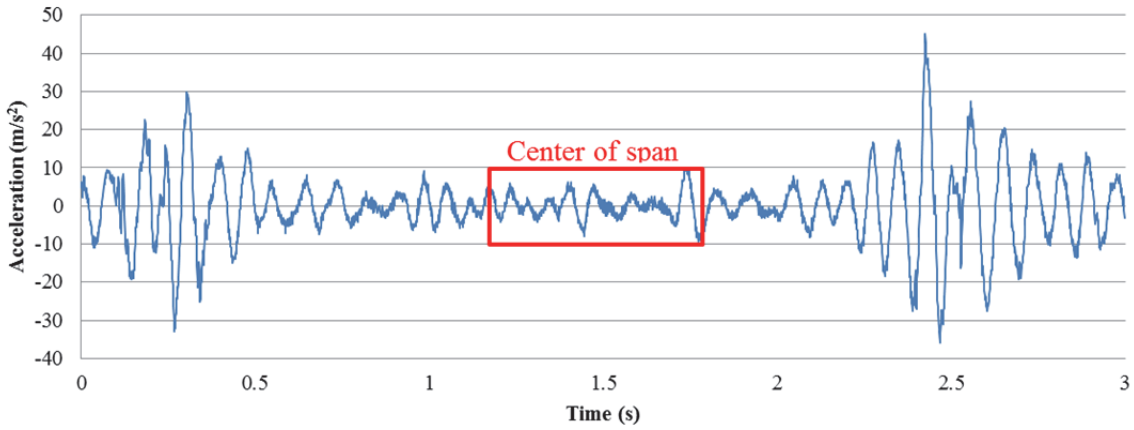

Figure 6. Vertical acceleration of center of span

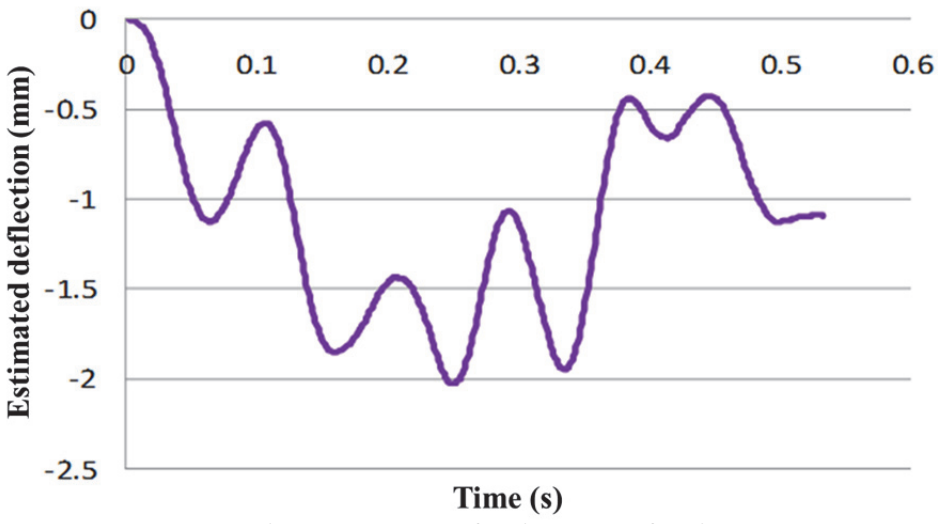

Figure 7. Result of estimated deflection

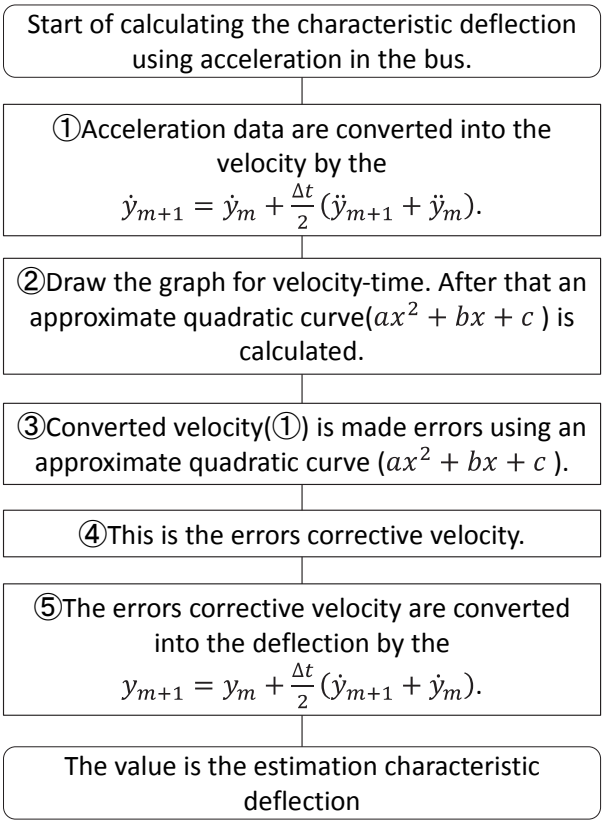

Figure 8. Flow of the calculating about the integrating two times of acceleration data

3. EXPERIMENTS OF THE BRIDGE MONITORING AT THE SAKAE BRIDGE

3.1 Outline of the experiment

As for this experiment, it was performed two times of plans of 10 Jan. 2013 and 11 Sep. 2012 with the Sakae Bridge that was a removal planned bridge. Specification of the Sakae Bridge is expressed as show in Table1. The bus run over the bridge and then "characteristic deflection" is calculated from the vertical acceleration under the rear wheel spring of the bus. The measurement conditions are shown in Table2. In this experiment, we are also investigating to influence "characteristic deflection" by the weight of vehicle. Then using vehicle is light vehicle and public city bus.

3.2 Outline of the monitoring sensor and measurement of environmental condition

Some acceleration sensors are installed in the vehicle under the rear wheel spring, the rear wheel axle center part. Location of sensor and photos are shown in Figure9 and Figure11 each vehicle. The compositions of the equipment to use for a measurement are show in Figure10, Figure12 respectively. Specification of the light vehicle and bus are show in Table3. Specification of the sensor is shown in Table4.

Table 1. Specification of the Sakae Bridge

Name	Sakae bridge	
Length	L=168.29 (m)	
Width	W=11.0 (m)	
Number of span	8	
Superstructure	Girder bridge (Gerber RCT)	
Substructure	Abutment : 2 unit	
	Rigid-frame pier (7 unit)	
Fundation structure	Abutment	Pine trees pile
	Pier	Open caisson
Year of construction	1941	
Traffic volumes (2005)	32100 /day	
Large vehicle (2005)	2.37%	

Table 2. List of the measurement conditions

	Measurement vehicle	Velocity (km/h)	Numeber of times
1st (11Sep.2012)	Bus	5	5
		10	5
		20	5
		30	15
	Light vehicle	10	3
		20	3
		30	3
		40	5
2nd (10Jan.2013)	Bus	20	5
		30	15
		40	5
	Light vehicle	20	5
		30	5
		40	5

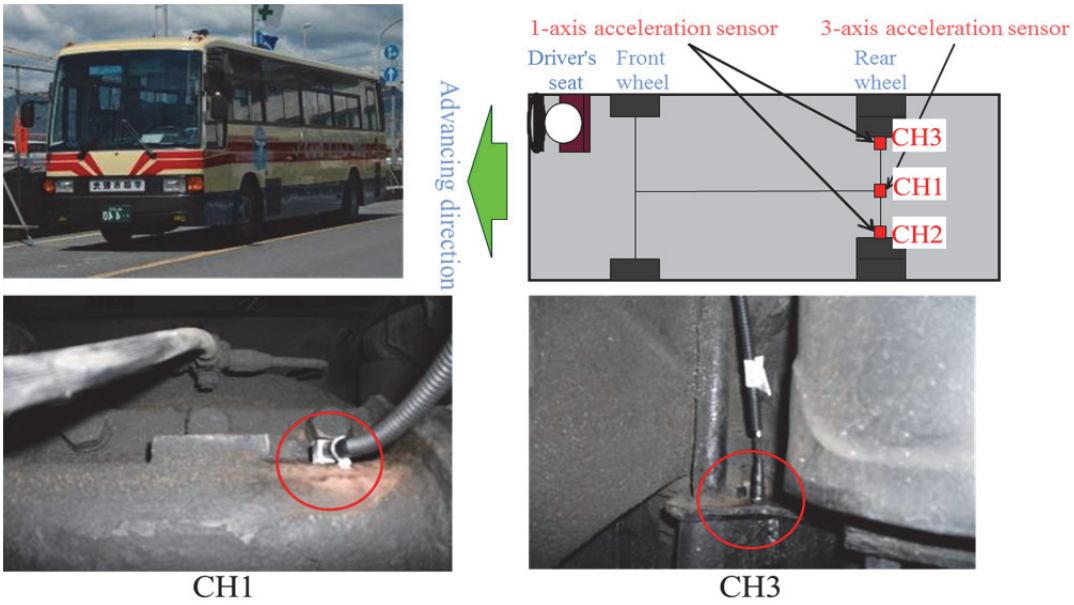

Figure 9. Location of sensors in the bus

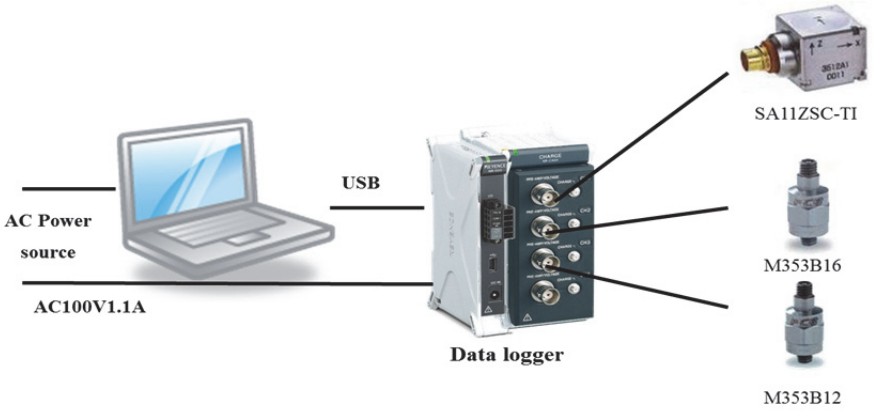

Figure 10. Composition of the equipment in the bus

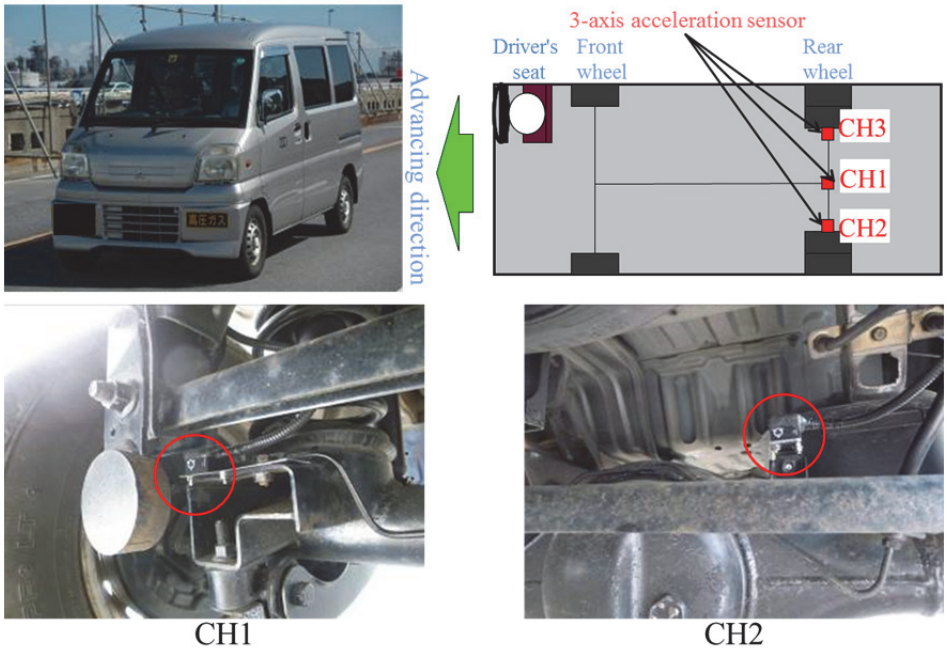

Figure 11. Location of sensors in the light vehicle

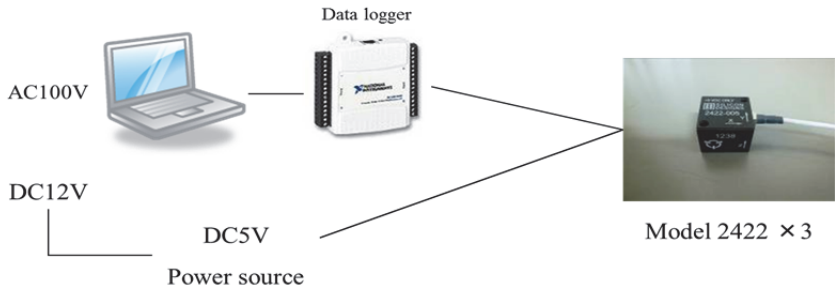

Figure 12. Composition of the equipment in the light vehicle

Table 3. Specification of vehicles

		Bus	Light vehicle
Riding capacity		57	2(4)
Length		1194 (cm)	339 (cm)
Width		249 (cm)	147 (cm)
Height		330 (cm)	189(cm)
Weight		11810 (kg)	860 (kg)
Gross weight		14945 (kg)	1320 (kg)
Axle-weight	Front	4030 (kg)	440 (kg)
	Rier	7780 (kg)	420 (kg)

Table 4. Specification of sensors

	Model number	Serial number	Channel	axis	Sensitivity of the sensor	Unit	Frequency response	Locations
Bus	SA11ZSC－TI	5692	CH1	z	0.99	mV/ms^{-2}	1-8000 Hz	Center
	M353B16	106161	CH2	z	1.058	mV/ms^{-2}	0.35-30000 Hz	Raight
	M353B12	106410	CH3	z	0.483	mV/ms^{-2}	0.35-30000 Hz	Left
Light vehicle	2422	1236	CH1	z	80.94	mV/ms^{-2}	0-400 Hz	Center
	2422	1237	CH2	z	81.05	mV/ms^{-2}		Raight
	2422	1238	CH3	z	81.27	mV/ms^{-2}		Left

4. EXPERIMENTAL RESULT

In this experiment, the evaluation of the span is No.2 from the Hiroshima side when characteristic deflection is calculated. The measured signals of the acceleration are divided by a peak signal based on passed a part of Gerber. As a shown in Figure13, upper side of figure is ground plan of span1 to span3 about Sakae Bridge. A Gerber part is located in Span2. In lower-left picture of Figure13, the rear wheel is passed, it is generated a peak signal by Gerber part. This peak signal is identified as moving to center of span. Then, in lower-right of Figure13, next Gerber part is passed by a vehicle, next peak signal is generated. As a result, complicated signal is divided.

4.1 A relation between acceleration of central sensor in the bus and acceleration on the bridge

The accelerometer on the bridge is located in the center of span2 as shown in Figure14. The response accelerations on the bridge when passed a vehicle are shown in Figure15. In this figure, it is verified that this bridge is vibrated by each vehicle. The strength of vibration by bus as shown in Figure15(a) is larger than by light vehicle in this Figure15(b). But, vibration by light vehicle is too smaller. As a result, it is not enough to vibrate by light vehicle.

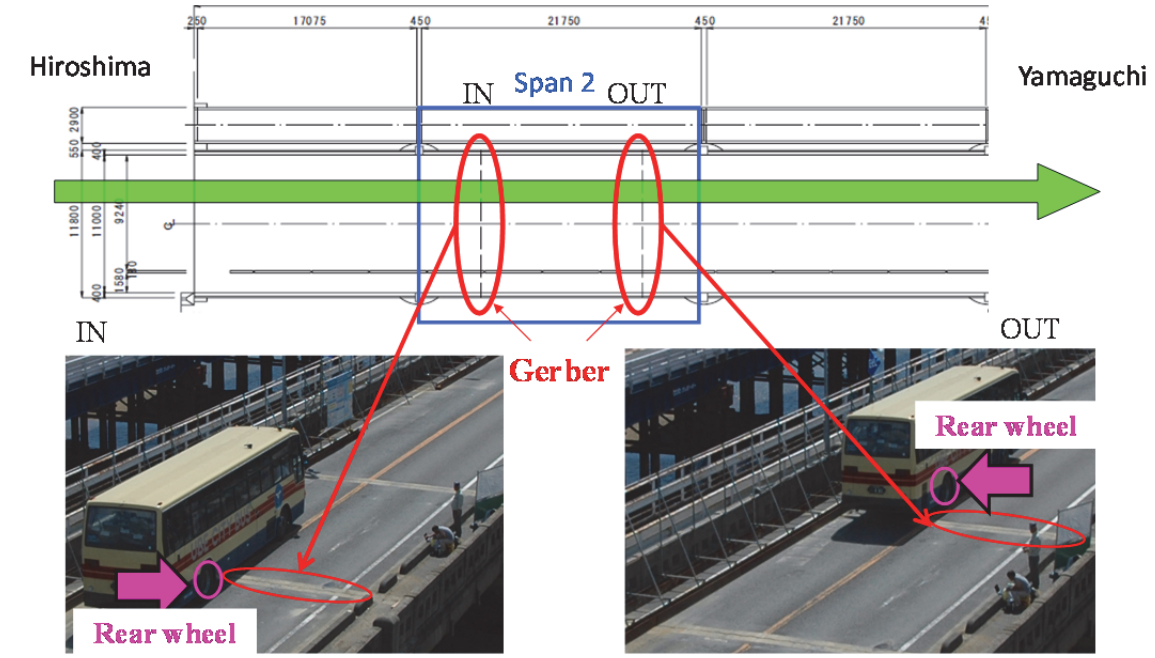

Figure 13. Identification of location of the signal based on passed Gerber part

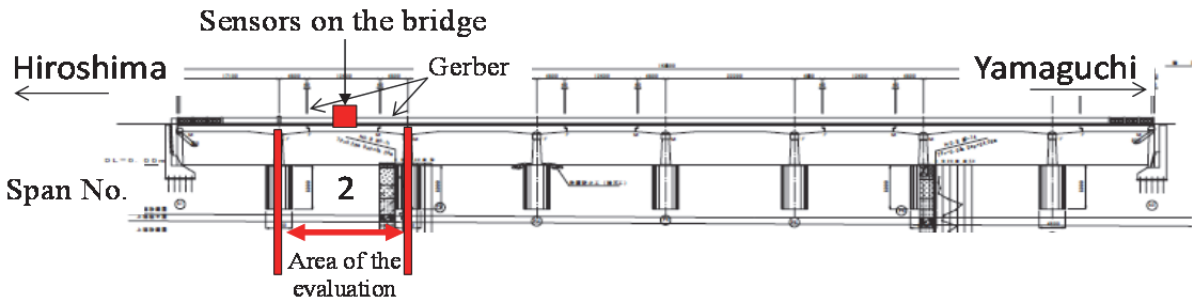

Figure 14. Measurement area and location of the sensor on the bridge

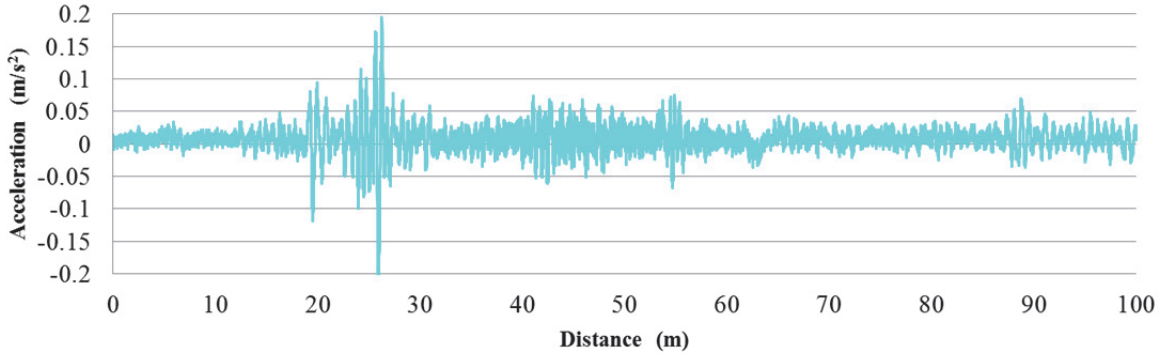

Figure 15. (a) The response acceleration on the bridge by bus

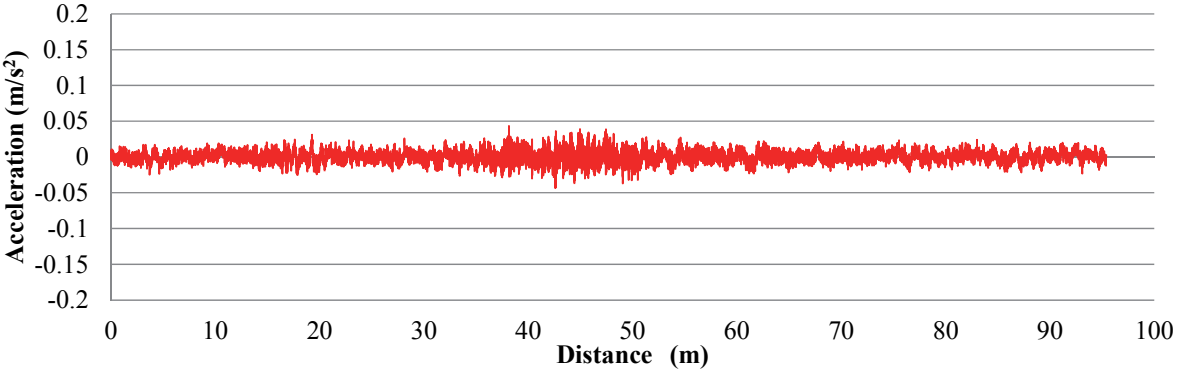

Figure 15. (b) The response acceleration on the bridge by light vehicle

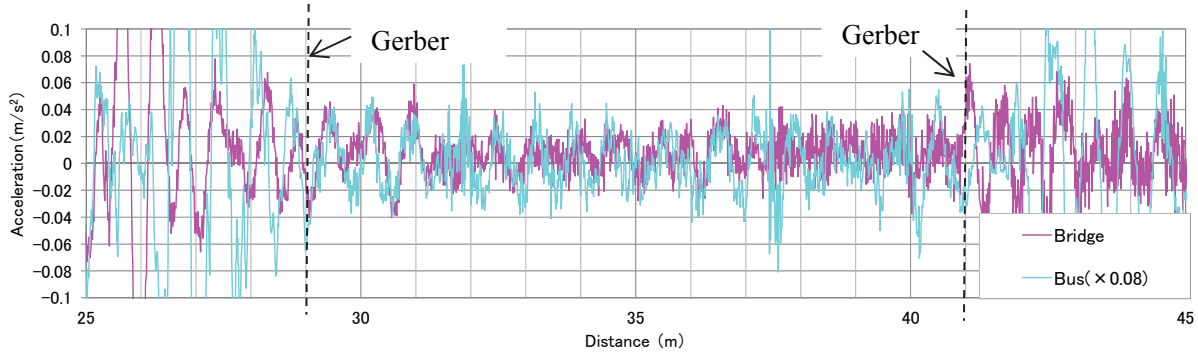

Figure 16. The comparison of vibration on the bridge and on the bus

The response acceleration on the bridge by bus and the vibration of rear wheel on the bus when passed the bridge is shown in Figure16. It is confirmed that the both wave patterns are similar when it is moving to Gerber part and passing Gerber part. Therefore, it is thought that the vibration property of the bridge from the rear wheel spring is able to be extracted by the acceleration of the bus.

4.2 The influence of the "characteristics deflection" on the location of sensor

In this chapter, by the each location of sensors about the influence of the "characteristic deflection" is discussed. The property of experiment is velocity of 30Km/h on the bus and area of the evaluation is Span2.

Firstly, the response acceleration on the bus as shown in Figure17 is discussed. The waveforms by the location of sensor are similar. In particular, peak signal each sensors as shown in rectangle of Figure17 is similar.

Next, the each sensor of location about “characteristic deflection” during 15 times measurements is shown in Figure18. As this graph is indicated than in spite of the difference of the sensor location, it became an about the same result.

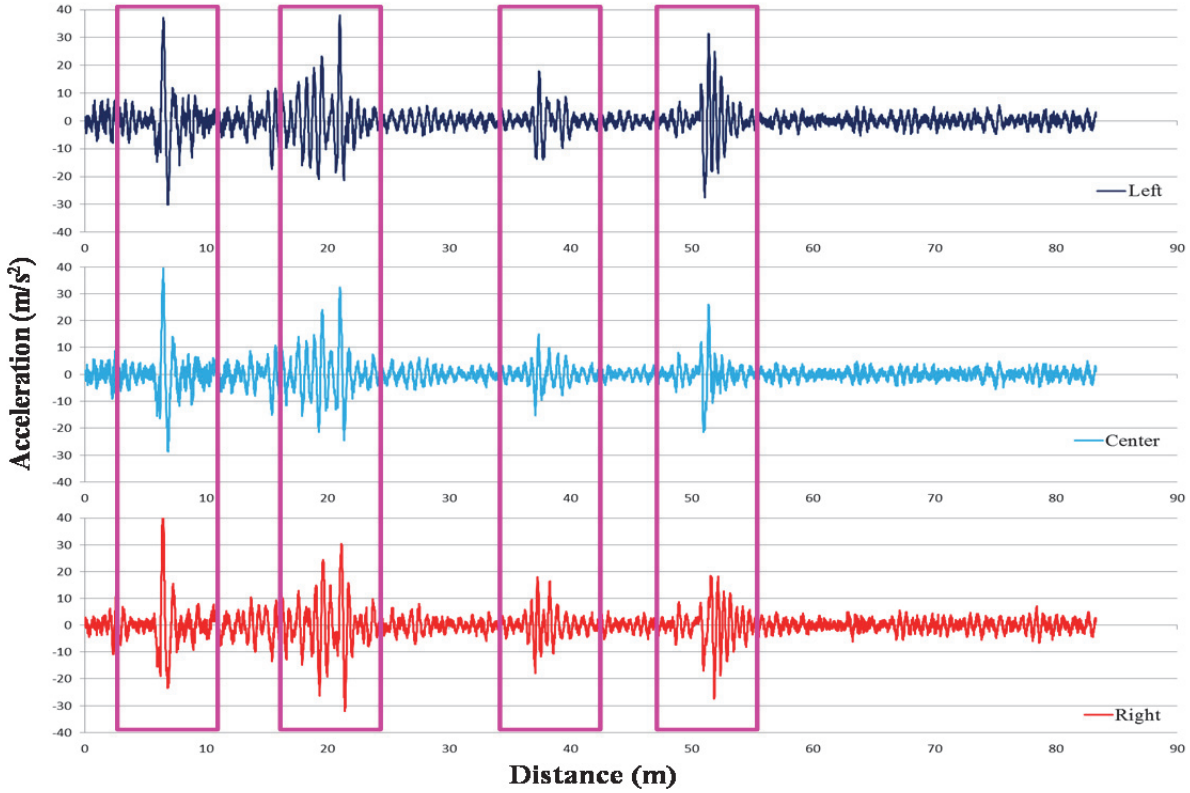

Figure 17.Eeach location of sensors about the response acceleration on the bus

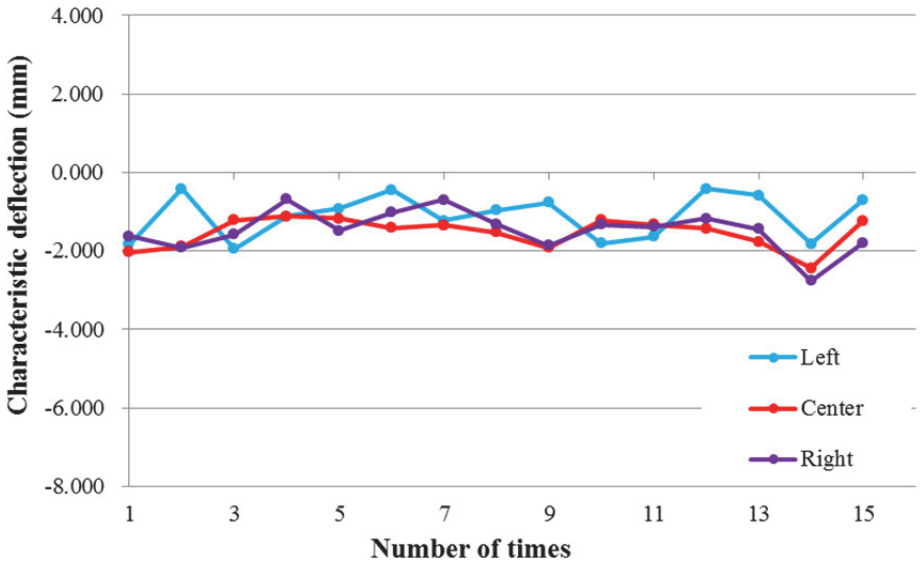

Figure 18. Each location of sensor about “Characteristic deflection”

Finally, it is found that when instrument is setting up, if there is it near rear wheel, “characteristic deflection” is not influenced on the any location of sensor.

4.3 The influence of the “characteristics deflection” on driving velocity

The influence of the “characteristics deflection” on driving velocity is discussed. The property of experiment about velocity is 10km/h, 20km/h and 30km/h using by the bus on center sensor at 1st experiment. This experimental result is shown in Figure19 about estimation deflection and Figure20 about “characteristics deflection”. These figures are indicated that lowest velocity (10km/h) is lowest value about estimation deflection and “characteristic deflection”. The reason why are because length of Sakae Bridge is 168m and roughness of road surface is directly transferred. When velocity is 20km/h and 30kim/h, waveforms are similar. However variety of the value at 20km/h is rather than

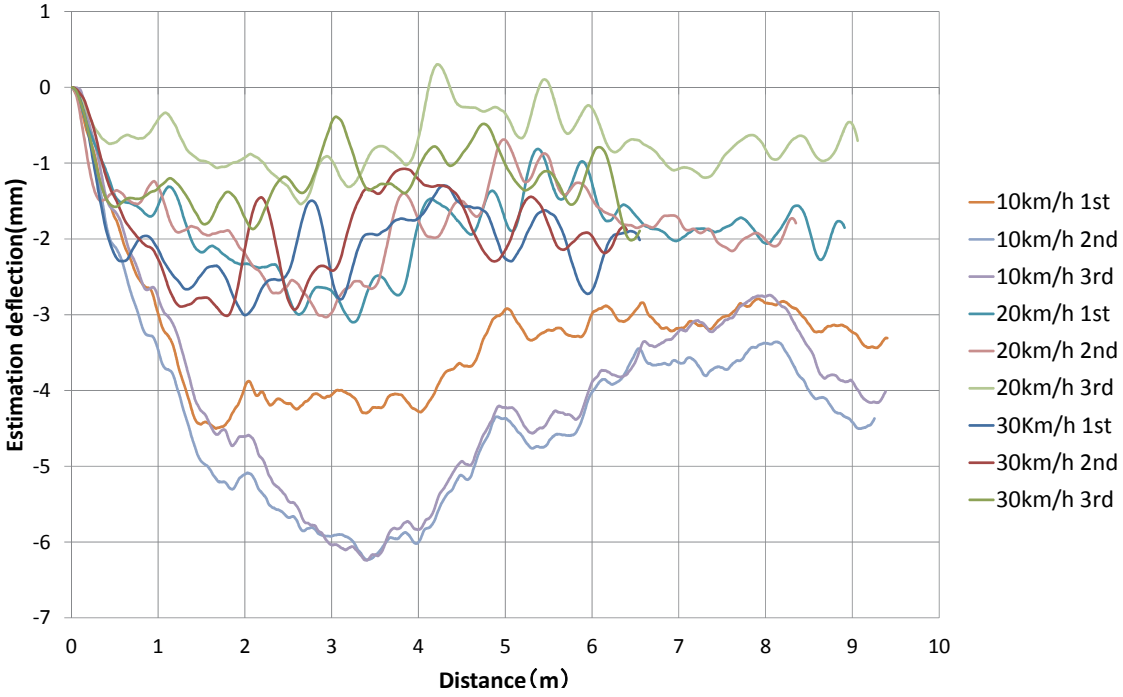

Figure 19. Each velocity about estimation deflection

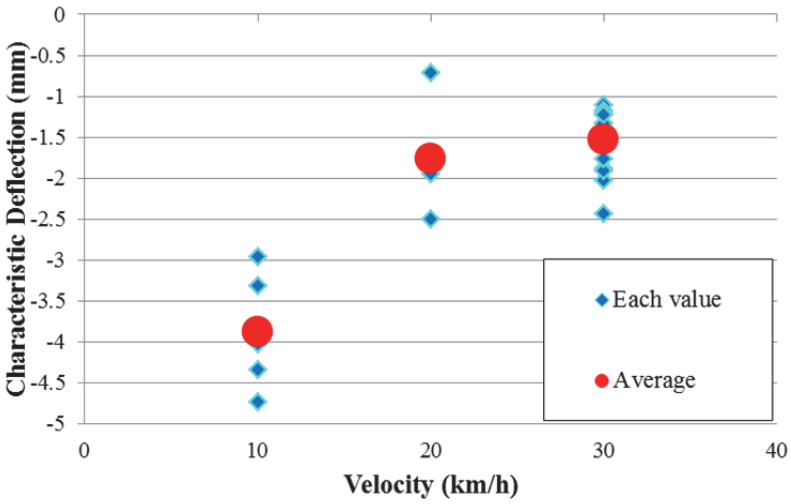

Figure 20. Each velocity about “characteristic deflection”

30km /h. The response frequency of the sensor may be influenced. As a result, driving velocity is influenced of the “characteristic deflection” and the driving velocity is better the 30km/h.

4.4 The influence of the “characteristics deflection” on seasons

The 1st examination is carried at 11 Sep. 2012, 2nd examination is carried at 10 Jan. 2013. The temperature of 1st is about 24℃, 2nd is about 4℃. A change of a season is the temperature. The difference of temperature is 20℃. We discussed that it is influenced of the “characteristics deflection”. In this experiment, the velocity is about 30km/h. As a result of “characteristic deflection” each seasons are shown in Table5. The difference of average of “characteristic deflection” is about 0.3mm. There for, the temperature is affected of “characteristic deflection”. Because, the temperature is grown up, the young modulus of road pavement is smaller. As a result, “characteristic deflection” is influenced on season.

4.4 The influence of the “characteristics deflection” on vehicle weight

The difference of weight of vehicle is over the 10 ton. Firstly, “characteristic deflection” of light vehicle is shown in Table6. In this table, center of “characteristic deflection” is smaller than another location (left or right). Because, the setting of center of sensor is not tightly, so the data of acceleration may include noise. However, “characteristic deflection” at the sensor of left or right is normally. In here, each of responses acceleration of bus and light vehicle is shown in Figure21. The strength of the signal from the light vehicle except peak signal is bigger than the signal of the bus. Because of the weight of light vehicle, it is influenced of roughness of road pavement during driving. Then the light vehicle vibrates up and down greatly. As shown in Figure15 (b), the bridge are not vibrated by light vehicle usefully. It means it does not take a load. And light vehicle tends to influence noise about roughness of road pavement and so on. As a result, the light vehicle is unsuited in order to measure the condition of the bridge.

5. CONCLUSION

In this study, bridge monitoring system using by public city bus which drives regularly is developed in order to maintain bridges effectively. Our country has a huge amount of bridges which were built for the rapid economic growth period that might become the acceleration period. This paper describes flow of maintenance about this monitoring system, procedure of evaluated data and discussing about influence of “characteristic deflection” on experimental property in real bridge. It was a removal

Table 5. List of “characteristic deflection” about seasons

Season		Locations		
		Left	Center	Right
Summer (11Sep.2012)	Average	-1.10906	-1.53718	-1.47175
	Standard deviation	0.549109	0.372703	0.496875
Winter (10Jan.2013)	Average	-0.8112	-1.2368	-1.1622
	Standard deviation	0.308214	0.318046	0.73156

Table 6. List of “characteristic deflection” using light vehicle

Locations / Times	Left	Center	Right
1	-0.8244	-2.1691	-1.2487
2	-1.8387	-3.6984	-1.4505
3	-1.1675	-6.3555	-0.8484
4	-1.7661	-4.2923	-1.8041
5	-1.2508	-3.3375	-2.6423
Average	-1.369484	-3.97055	-1.598805
Standard deviation	0.3819509	1.379259	0.6064013

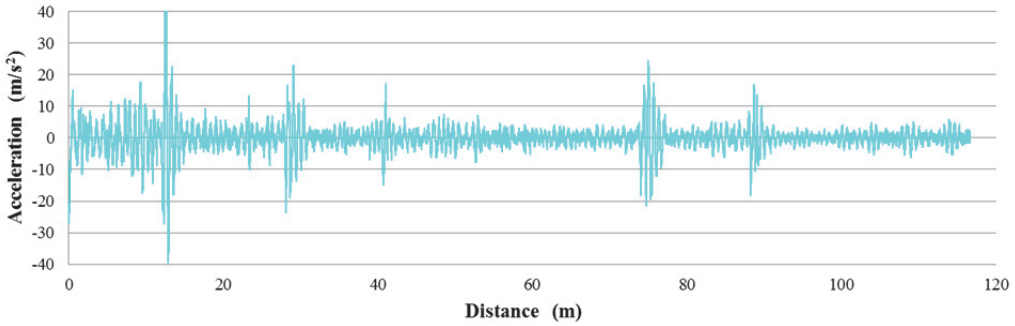

Figure 21. (a) The response acceleration on the bus

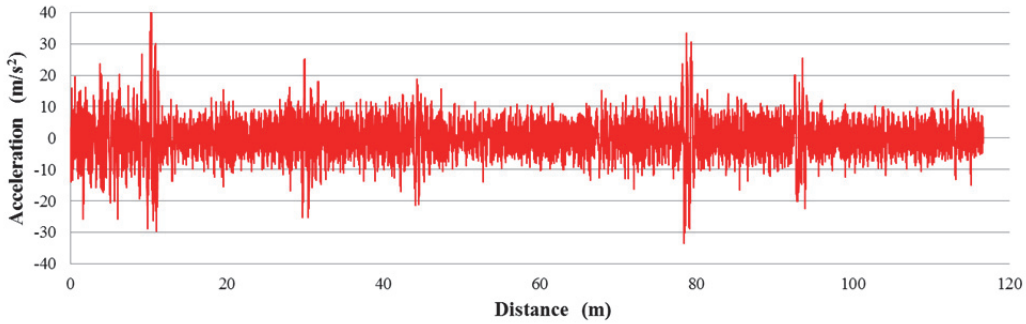

Figure 21. (b) The response acceleration on the light vehicle

planned bridge by the measurement with the real bridge and was able to perform the measurement with various cases because it was the situation that other vehicles did not pass. The following results were obtained:

1) It is found that location of sensor which sets up side of right, center and left does not influence of "characteristic deflection". But the sensor sets under the suspension at rear wheel.
2) It is found that the difference of driving velocity influenced of "characteristic deflection". In particular, when driving velocity is 30km/h and 10km/h, difference of "characteristic deflection" is very huge.
3) It is found that the season (temperature) is affected of "characteristic deflection.
4) It is found that weight of vehicle influenced of "characteristic deflection". And light vehicle tends to influence noise about roughness of road pavement.

In the future, we need to develop method of correct the evaluation data under the environmental measurement.

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