# DYNAMIC RESPONSE OF TRACK TYPE BRIDGE FOR BIMODAL TRAM THROUGH SPEED INCREASING TEST

E. Cho<sup>1</sup>, E. Bae<sup>1</sup>, H. Kim<sup>2</sup>, W. Hwang<sup>2</sup>\*

<sup>1</sup> Department of Infrastructure, Hyundai Engineering, Seoul, Korea
 <sup>2</sup> Department of Civil Engineering, INHA University, Incheon, Korea
 \* Corresponding author(hws@inha.ac.kr)

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# **1** Introduction

A bimodal tram is the new public transportation system that makes up for the weakness of the conventional transportation system such as the bus and the subway. This system has advantage of running on the exclusive and the general road. A pipe truss bridge for the bimodal tram can have a long span because of the effect of self-weight reduction of the system. However, an analysis of dynamic response characteristics should be required because this new type bridge has never been constructed before. In present study, the estimation of dynamic response characteristics is performed by comparing with the displacement and the maximum acceleration of the bridge in the experiment and the numerical method. A speed increasing test for the bridge was conducted with sensors at the bottom of the bridge. Also, dynamic response characteristics were analyzed by the vehicle-bridge interaction analysis.

# 2 Speed Increasing Test

## 2.1 Bridge Descriptions

As shown in Fig.1, the exclusive bridge for bimodal tram, which was studied in this research, is located in Milyang Test Road and is a simply supported single-span bridge with the total length of 16.6m. The bridge type is steel pipe truss. The width of bridge is 8.7m, and the height of girder is 1.6m.





Fig.1. Exclusive pipe truss bridge for Bi-modal tram

# 2.2 Bimodal Tram Properties

The vehicle for the speed increasing test is a bimodal tram with 3 wheel axes. It is 18.0m long, 2.5m wide and 3.4m high. Load per wheel axis is 65.7kN ( $1^{st}$  axis), 89.3kN ( $2^{nd}$  axis) and 90.3kN ( $3^{rd}$  axis) respectively, the distance between wheel axes is 7.7m and 7.5m.



Fig.2. Dimension of Bi-modal tram

#### 2.3 Instrumentation and Experiment Procedure

In this test, accelerometers and LVDTs were used for investigating dynamic characteristics according to the vehicle speed.

Accelerometers were installed vertically and horizontally on the center and 1/4 point of the bridge span. The accelerometers can measure within the maximum range of 5g.

In order to examine the displacement response of the bridge, LVDTs were installed on the center and 1/4 point of the bridge span, one in the vertical direction and another in the horizontal direction, and their maximum range of measurement is 10 mm.

The speed increasing test began with static loading on the center and the supports of the bridge, starting from 5 km/h and increasing by 10 km/h.



Fig.3. Sensor location

Table.1. Sense	ors per attach	ment points
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Location	Sensors	Direction	Quantity
	Accelerometer	Vertical	1
А	LVDT	Horizontal	1
	Strain gauge	Longitudinal	1
В	Accelerometer	Vertical	1
	Accelerometer	Vertical	1
С	LVDT	Vertical	1
	Strain gauge	Longitudinal	1
D	Strain gauge	Axial	1



Fig.4. Sensors attachment at the center of the bridge



Fig.5. Speed increasing test on the bridge

#### **3** Vehicle-Bridge Interaction Analysis

#### 3.1 Vehicle Model

After deriving kinetic energy, potential energy of springs, and dissipated energy of dampers for a vehicle, the vehicle matrix can be defined by Eq. (1), which is derived as a type of Euler equation based on the Hamilton principle.

$$\frac{d}{dt} \left( \frac{\partial T_i}{\dot{q}_i} \right) - \frac{\partial T_i}{\partial q_i} + \frac{\partial V_i}{\partial q_i} + \frac{\partial D_i}{\partial \dot{q}_i} = F_i$$
(1)

Where, T, V, and D represent the total kinetic energy, potential energy, and dissipation energy of vehicles, respectively



Fig.6. Numerical model of Bi-modal tram

Table.2. Notations of vehicle

Description	Notation
Mass of front and rear car-body	$m_{11}, m_{22}$
Moment inertia of car-body	$I_{x11}, I_{x22}, I_{y11}, I_{y22}$
Displacement of car-body	$x_{v1}, x_{v2}, z_{v1}, z_{v2}$
Rolling, pitching of car-body	$ heta_{vx1}$ , $ heta_{vx2}$ , $ heta_{vy1}$ , $ heta_{vy2}$
Spring constant of suspension	k <sub>v3ij</sub> , k <sub>v143</sub>
Damping constant of suspension	C <sub>v3ij</sub> , C <sub>v143</sub>

## 3.2 Bridge System

The analysis model for the bridge is idealized using 3D space frame elements in which it is assumed that the slab is strongly coupled to the girder. The road profiles are estimated using the power spectral density (PSD) for the transverse and longitudinal direction. The road profiles can be written as follows.

$$r(t) = \sum_{k=1}^{N} \sqrt{4S(f_k)\Delta f_k} \cos(2\pi f_k s - \theta_k)$$
(2)  
Where,  $\Delta f_k = \overline{f_h} - \overline{f_{h-1}}, \quad f_k = \frac{1}{2}(\overline{f_h} + \overline{f_{h-1}})$ 





Fig.7. Numerical model of the bridge

#### 3.3 Coupled Equations of Forced Vibration for Vehicle-Bridge Interaction Analysis

The equation of motion of the forced vibration of the bridge can be expressed as follows:

$$[M_{b}]\{\ddot{q}\}+[C_{b}]\{\dot{q}\}+[K_{b}]\{q\}=\{f_{b}\}$$
(3)

Where,  $[M_b]$ ,  $[C_b]$  and  $[K_b]$  show the mass, damping, and stiffness matrix of the bridge, respectively.

Also, ( $\cdot$ ) shows the differentiation with respect to time. The right term of Eq. (3),  $\{f_b\}$  means the applied load to the bridge through the contact points between the wheels and the bridge and can be written as follows:

$$\{f_b\} = \sum_{\nu=1}^{n\nu} \sum_{k=1}^{a} \sum_{n=1}^{b} \sum_{u=1}^{c} \Psi_{\nu 2knu} P_{\nu 2knu}(t)$$
(4)

Where,  $\Psi_{v2knu}$  is a load distribution vector, and  $P_{v2knu}$  shows the wheel load of the vehicle and can be defined according to x, and y directions.

The equation of motion of the forced vibration of Eq. (3) can be presented in the coupled matrix form as follows [3]:

$$\begin{bmatrix} M_{b} & 0\\ 0 & M_{v} \end{bmatrix} \left\{ \ddot{a} \right\}^{+} \begin{bmatrix} C_{b} + C_{v}(t) & C_{bv}(t)\\ C_{bv}^{T}(t) & C_{v} \end{bmatrix} \left\{ \dot{a} \right\}$$

$$\begin{bmatrix} K_{b} + K_{v}(t) & K_{bv}(t)\\ K_{bv}^{T}(t) & K_{v} \end{bmatrix} \left\{ q \right\} = \left\{ f_{b} \right\}$$

$$(5)$$

Where,  $C_{\nu}(t)$ ,  $K_{\nu}(t)$  are the characteristic values of the primary suspension in the vehicle, which are coupled with damping and stiffness matrix of the bridge, and  $[C_{b\nu}(t)]$ ,  $[K_{b\nu}(t)]$  are the characteristic matrix of the primary suspension in the vehicle that is related to the degree of freedom of the vehicle in their interaction forces.  $[C_{b\nu}^{T}(t)]$ ,  $[K_{b\nu}^{T}(t)]$  are the part composed from inertial force of interaction forces. In addition,  $[M_{\nu}]$ ,  $[C_{\nu}]$  and  $[K_{\nu}]$  represent the mass, damping, and stiffness matrix of the vehicle, and The solutions of the equations of motion of (5) are drawn from Newmark  $\beta$  [4] and the solutions of coupled equations of motion are calculated by composing effective stiffness matrix and effective force vector by analysis time step.

#### 4 Dynamic Response of the Bridge

#### 4.1 Natural Frequency of the Bridge



Fig.8. Excitation Point by Impact Hammer for Measuring a Natural Frequency of the Bridge

As shown in Fig.8, the natural frequency of the bridge is measured by hitting the center point of the lower chord by impact hammer. The measured data gained from the impact test are converted into a frequency domain by Fast Fourier Transformation (FFT) technique. The estimated natural frequency of the bridge from the test is 7.75 Hz. This result agrees with the analysis result of 7.80 Hz.



Fig.9. Natural Frequency of the Bridge by Impact Test

4.2 Determination of Damping Ratio through Impact Hammer Test



Fig.10. Estimation of Damping Ratio

It is very difficult that a damping ratio of structures is determined by analytical methods. Therefore, a damping ratio should be determined by experiments. The damping ratio of the bridge can be estimated by Eq. (6) base on the acceleration data gained from the speed increasing tests and impact tests.

$$\zeta = \frac{1}{2\pi j} \ln \frac{u_i}{u_{i+j}} = \frac{1}{2\pi j} \ln \frac{u_i}{u_{i+j}}$$
(6)

As shown in Fig.10, the damping ratio of the bridge converges on 1.4

## **4.3 Dynamic Response Characteristics by Speed Increasing Test on the Bridge**

The analysis results are verified by using the displacement time history at the mid-span of the bridge and the maximum acceleration responses in vertical and lateral directions resulted from experiments.



(b) Comparison of peak value of vertical acceleration



Fig.11. Comparison of analytical and experimental results

### **5** Conclusions

Present study performed the estimation of the dynamic response of the steel pipe truss bridge for bimodal tram by the experiment and the numerical analysis. The major results of this study can be summarized as follows:

1. The reliability of the estimation of the dynamic response of the bridge is verified by comparing with the test and the numerical analysis results.

2. As the vehicle speed increases, the maximum transverse and longitudinal acceleration response slightly increases. Also, the maximum vertical displacement of the bridge is 1.5mm at the vehicle speed of 60km/h.

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