Resonant Bridge Detection Method by On-board Measurement

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Large vibrations due to resonance is a major issue for high-speed railway bridges. In order to efficiently and frequently inspect bridge resonance, this study proposes a detection index, amplification factor, based on the vertical acceleration of the head and tail vehicles of a passing train. Field tests with actual trains and bridges revealed that the amplification factor tends to increase with bridge resonance and the impact factor. In addition, train-bridge dynamic interaction simulation clarified that the correlation of the amplification factor with the impact factor was over 0.9. It also revealed that the amplification factor of a train with short vehicles could be used to detect the potential resonance of bridges.

Keywords: resonance, railway bridge, on-board measurement, car body acceleration

1. Introduction

Railway bridge resonance occurs when the excitation frequency corresponding to the regularly arranged axles of traveling trains are close to the bridge frequency. Considering recent increases in train speed, low rigidity of structures and long span bridges, it is difficult to avoid resonance on high-speed railways. Dynamic response amplification from resonance is also considered in bridge design as an impact factor, and resonance itself is not problematic. However, if very large bridge vibrations occur that exceed initial assumptions about resonance, it can cause serious maintenance problems such as progressing cracks and fatigue damage [1].

In order to detect resonant bridges or estimate bridge deflections, in-situ bridge displacement measurements have been conducted from the ground. However, in-situ measurements for a large number of bridges is time and labor intensive and requires significant economic resources, in addition to the constraints related to the location and access conditions under bridges [2]. Furthermore, tracking structural change over time, calls for frequent measurements or continuous monitoring. As such, installation of monitoring equipment in the practical field also requires considerable initial investment and subsequent management of the monitoring equipment itself [3].

Comprehensive collection of bridge data by trains equipped with sensors mounted on vehicles passing through every day is a much more effective primary screening method. Bridges that require further investigation can then be extracted from the large number of bridges monitored by on-board measurements optimizing use of resources required for maintenance. Also, frequent inspections using on-board measurements can help mitigate risk in the periods between bridge inspections.

This study proposes a detection index for primary screening, focusing on the vertical acceleration of travel-

ing vehicles as a method for on-board resonant bridge detection. The relationship between the proposed index and bridge impact factor is verified by on the actual train running test. Furthermore, the possibility of potential resonant bridge detection is examined by a vehicle-bridge interaction simulation that can reproduce the measured values. It should be noted that only the impact factor α related to the effect of speed of moving loads is considered in this study.

2. Concept and methods

2.1 Resonance of railway bridges and proposed detection index

To understand the outline of resonance, Fig. 1 shows numerically calculated bridge displacement responses, head and tail vehicle acceleration responses for each train speed for a typical resonant railway bridge. As shown in Fig. 1, as train speed increases, by the periodic excitation based on the regular axis arrangement of passing trains, bridge dynamic response amplification occurs and the impact factor increases. In case of Fig. 1, the resonance with maximum impact factor occurs at 295 km/h. Resonance speed can be calculated based on the bridge frequency 3.3 Hz and vehicle length 25 m as $25 \times 3.3 \times 60 \times 60 \div 1000 = 295$ km/h [1]. Once the resonance speed is exceeded, bridge dynamic response amplification again decreases. A beat phenomenon occurs at speeds before and after full resonance. When the beat occurs, maximum displacement is reached when the intermediate vehicle passes over the bridge.

As shown in Fig. 1, when the running train and bridge resonate completely, the dynamic response of the bridge gradually increases as the train passes. In order to capture this effect, this paper proposes a detection index that uses two vertical acceleration responses measured on the head

Fig. 1 Impact factor of resonant bridge, bridge displacement responses and head and tail vehicle vertical acceleration responses for each train speed

and tail vehicles. This presupposes the use of the accelerometers already installed in the vehicles to manage track irregularity.

In the case of no resonance, the bridge behaves in a quasi-static manner with an almost total absence of dynamic amplification. This means that the bridge displacements corresponding to the head and tail vehicles are almost same. Therefore, car body vertical acceleration amplitudes of the head and tail vehicles at the low-frequency are also similar, and the ratio (tail / head) is close to 1.

On the other hand, when full resonance occurs, bridge displacement gradually increases as the train passes, as shown in Fig. 1. This displacement, when the tail vehicle passes, is greater than the displacement when the head vehicle passes and excitation from the bridge displacement causes higher car body vertical acceleration in the tail vehicle. Therefore, the tail / head acceleration ratio exceeds 1.

Based on the above, this study attempts to detect resonant bridges using an index based on the filtered car body vertical accelerations of the head and tail vehicles. The vertical acceleration time series responses from bridge entry to the exit measured by the head and tail vehicles are represented as vectors $\mathbf{x}_H$ and $\mathbf{x}_L$. An amplification factor C_a expressing vertical acceleration amplification between these vehicles is defined by (1).

$$C_a = \frac{\sqrt{\mathbf{x}_L^T \mathbf{x}_L}}{\sqrt{\mathbf{x}_H^T \mathbf{x}_H}} \quad (1)$$

Equation (1) means the ratio of root mean squares (RMS) of the body accelerations of the tail and head vehicles. In addition to the RMS, the maximum and minimum accelerations were also separately examined, however the RMS was finally adopted in consideration of the effects of high-frequency noise caused by the vehicles and track irregularities and electronic equipment.

2.2 Target bridges

Table 1 shows the specifications of the bridges employed in this study. This study focused on three types of concrete railway bridges with span lengths of 23 - 48.6 m

Table 1 Specifications of target bridges

ID	Girder type	Span L_b (m)	Girder height (m)	Concrete Young's modulus (kN/mm ²)	Frequency (Hz)	Resonance speed (km/h)
A	T	23.0	1.7	55.8	5.58	502
B	T	34.2	2.0	58.9	4.45	401
C	Box	48.6	3.0	43.4	2.78	250

Fig. 2 Cross section of target bridge C (unit: mm)

in which a full-scale train running tests were conducted [2].

Figure 2 shows the cross-sectional view of bridge C. The Young's modulus and natural frequencies shown in Table 1 are the values updated by the identification analysis based on the measured bridge displacement responses with passing trains [4].

2.3 Measurement method

Bridge displacements and car body accelerations were measured on actual bridges and trains during tests to increase running speeds before the opening of a new high-speed line [2]. Bridge displacements at mid-span when the train passed at 200 and 260 km/h, were measured using a ring displacement meter or video measurements. The bridge impact factor was calculated through numerical simulation that reproduces these measured values well, as described later. Car body vertical accelerations were measured by accelerometers installed on the floor of head / tail vehicle car bodies just above the first / second bogies of

Fig. 3 Numerical models

a 10-car train. The car body accelerations were measured when the train was traveling at speeds of 110 km/h to 260 km/h increased at approximately 20 km/h intervals. Measured and 100 Hz low-pass filtered acceleration time series responses were converted to a function of distance (position) with 40 mm sampling.

2.4 Numerical calculation method

Figure 3 shows the vehicle and bridge models used in the numerical simulation. The vehicle and structure were modeled using multibody and finite element systems, respectively. The calculations were performed using the simulation program DIASTARS III. Readers interested in details should refer to [1]. Parameters of the vehicle model were set based on recent high-speed vehicle specifications. The structural model was constructed using Timoshenko beam elements for bridges and rails, and spring elements as track pads. DIASTARS III modifies the motion equations of vehicles and structures respectively. The equation of motion on the modal coordinate system is solved in units of time increment Δt by Newmark's average acceleration method. Δt was set to 0.0001 seconds as a standard, and the maximum modal order was set to 50th considering rail deformation modes. All modal damping ratios were set to 2%.

3. Results of experiments

3.1 Measurement results of car body acceleration

Figure 4 shows the acceleration responses of the head and tail vehicles when passing over bridges A and C. The results given have been processed through a low-pass fil-

Fig. 4 Vertical acceleration responses on the car body floor when passing over bridges

ter. The accelerations on the car body floor when passing over the bridges vary from negative to positive sides when entering and exiting the bridge. This is a characteristic of a typical acceleration wave, when a moving mass passes over sagging bridges [5]. This fact indicates that components caused by the flexural deformation of the bridge are included in the car body acceleration wave at least at a distinguishable level.

The tail vehicle had a slightly larger acceleration than the head vehicle even when train traveling at 200 km/h. Increasing the traveling speed to 250 km/h, revealed that the acceleration amplitudes of the tail vehicle at bridges A and C increased significantly compared to the head vehicle. Thus, if resonance occurs in bridges A and C when traveling at 250 km/h, it can be verified that the amplification factor C_a in equation (1) is effective for resonant bridge detection. It should be noted that the maximum vertical acceleration of the car body used for ride comfort evaluation is 0.25 g (= 2.45 m/s²) for full amplitude [6]. The target accelerations have a maximum of approximately 0.7 m/s². Therefore, it can be understood that the vertical acceleration considered in this study is within a level of vehicle vibration that does not cause a ride comfort problem.

3.2 Estimation results of amplification factor C_a

Figure 5 shows the relationship between train speed and the amplification factor C_a calculated by (1) based on the measured car body accelerations at each train passage over the bridge. The figures also show bridge impact factors calculated by the simulation described later.

As for bridges A and C, where significant amplifications of on-board measured accelerations were observed in the tail vehicle when travelling at 250 km/h, the impact factors of these bridges had peaks corresponding to the secondary and primary resonances. In the case of bridge C in particular, the impact factor and the amplification factor C_a around the primary resonance showed the same amplification tendency. In addition, the increase of the amplification factor C_a can be confirmed at the secondary resonance

Fig. 5 Measured amplification factors C_a and numerically simulated impact factors

speed in the down bound train in bridges A and B. On the other hand, amplification factors C_a for the up and down bound trains in bridges A and B were inconsistent. This is considered to be due to the adjacent bridge effect. However, the purpose of this study is to clarify the basic characteristics of the amplification factor C_a and impact factor from trains passing over bridges. Therefore, the influence of adjacent bridges will be dealt with in another study.

3.3 Results of numerical simulation and verification

Actual measurements limit the test range of train speed and impact factor, and actual field tests include various influences such as adjacent bridges and track irregularities. Here, numerical simulations are performed to analyze the basic relationship between the impact factor of bridges and the amplification factor C_a of vehicles while eliminating these various influences.

Figure 6 shows the measured and simulated displacement responses at bridge mid-span with a passing train. The concrete Young's modulus identified from the measured frequencies were given to the bridge simulation model [4]. The input values are shown in Table 1. The impact factors shown in Figure 5 were calculated by this model. The simulated displacement responses were reproduced well.

Figure 7 shows the measured and simulated amplification factor C_a for when trains were passing over the bridges. In case of the simulation, the amplification factors C_a were calculated after filtering the car body vertical acceleration of the head and tail vehicles when passing over the bridge in the same manner as with the measurements. Although the measured values vary widely for the bridge

Fig. 6 Comparison of measured and simulated bridge displacements (bridge C)

Fig. 7 Comparison of measured and simulated amplification factor C_a

B, the simulated C_a generally agreed with the measured values for bridges A and C. Therefore, it can be considered that the constructed numerical models can accurately reproduce the dynamic response of the bridge when a train passes over it, and that of the vehicles when passing over the bridges. The reason why the measured values vary on bridges A and B could be considered to be due to the adjacent bridge effect, which was not considered in the numerical simulation.

3.4 Discussion about detection performance

Figure 8 shows the impact factor and amplification factor C_a relationship calculated by numerical simulation for traveling speeds of 100 - 400 km/h. The impact factor and amplification factor C_a showed a high positive correlation exceeding 0.9 for all bridges. A high tendency of proportionality between the amplification factor C_a and the impact factor is observed in high impact factor region. Figure 8 also shows first-order approximation lines for the impact factors and amplification factor C_a of each bridge. Focusing on C_a with the same impact factor, we see that the bridges with a longer span tended to produce a larger amplification factor C_a . This means that the tail vehicle response passing through shorter span bridges is not as amplified

Fig. 8 Numerically calculated amplification factor C_a and impact factor

as when passing over longer span bridges. Figure 8 shows that the amplification factor C_a hardly changes in a region with small impact factors. The region where the amplification factor C_a does not change is larger as the span length is shorter. It means that the sensitivity of the amplification factor C_a to the increase in impact factor decreases as the bridge span becomes shorter.

Based on these simulation results, the linear relationship between the impact factor and the amplification factor C_a is effective in the region of impact factors more than 0.5, 0.7, and 0.9 for the bridge C with 48.6 m span, bridge B with 34.2 m span, and bridge A with 23.0 m span, respectively.

3.5 Detection of potential resonant bridges

So far, the study has focused on the detection of resonant bridges based the measurement results using commercial trains. However, the extraction of potential resonant bridges where resonance may occur in future has a greater practical contribution in terms of considering countermeasures in advance [7]. Here, the feasibility of the potential resonant bridge detection using a train composed of shorter vehicles (vehicle length 20m) relative to high-speed rail vehicles in general (vehicle length 25m), was verified through numerical analysis. The train consisted of 20-meter long vehicles, like the typical track inspection trains that are already in use [8].

Figure 9 shows the impact factors of the bridge and the amplification factor C_a of the passing train numerically calculated for a bridge with 30 m span length. The impact factor and the amplification factor C_a were observed on two types of train: a train with 12x25-meter long vehicles and a train with 6x20-meter long vehicles, travelling at a speed of 240 km/h. The horizontal axis expresses the bridge frequency. Assuming a decrease in bridge frequency with age, deterioration, and damages, the horizontal axis was set so that the frequency decreased towards the right side.

The amplification factor C_a in the case of the train with 25-meter long vehicles showed a tendency similar to the impact factor as the result of examinations up to the previous sections. It can be inferred that the increasing tendency of the amplification factor C_a can allow us to detect the resonant bridges with 2.8 Hz frequency and 1.9 impact factor. On the other hand, with the train with 6x20-meter long vehicles, the amplification factor peaked peak at approximately 2.8 Hz, which is higher than the 2.7 Hz bridge

Fig. 9 Influence of vehicle length on detectable impact factor (span: 30 m, speed: 240 km/h)

frequency, because the vehicle length was shorter than the high-speed railway vehicles. The increasing tendency of the amplification factor C_a obtained in 20m vehicle can be expected to enable us to detect potentially resonant bridges with a frequency of approximately 3.0 Hz and impact factor of 0.92. Therefore, it is possible to detect the bridge before resonance occurs of by using the amplification factor of the inspection vehicle in combination with a shorter vehicle length. However, it should be noted that the amplification factor of the train with shorter vehicle length tends to be smaller than that of commercial train and is easily affected by track irregularities.

4. Conclusions

In order to detect resonant bridges using acceleration response measured with equipment on running vehicles, this study proposes a detection index of resonant bridges, and reports on trials using on-board and in-situ measurements from actual train running tests and numerical simulation considering the vehicle-bridge dynamic interaction. The following findings were obtained in this study.

- (1) Focusing on the vertical acceleration of vehicles running on resonant bridges, we find that the ratio of the car body acceleration RMS of the head and tail vehicles, amplification factor C_a , was proposed as a detection index of the resonant bridge.
- (2) On board and in-situ train and bridge measurement results in the actual train running tests show that the proposed amplification factor C_a can be used to detect resonant bridges because it increases along with the impact factor when bridge resonance occurs.
- (3) The numerical study indicates that the amplification factor C_a has a correlation of over 0.9 with the impact factor, and C_a manifests a dependence on the bridge span length. Specifically, bridges with longer spans produce a larger amplification

factor $C\alpha$ even if the impact factors are the same.

- (4) A numerical study clarified that the amplification factor $C\alpha$ of trains with shorter vehicle length (20 m) can be used to detect potential resonant bridges before significant vibrations occur due to resonance.

In order to for the amplification factor $C\alpha$ to be applied in practice as a detection index for resonant bridges, in addition to the results of this study, it is necessary to verify the effects of adjacent spans and track irregularities.

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References

- [1] Sogabe, M., Matsumoto, N., Fujino, Y., Wakui, H., Kanamori, M. and Miyamoto, M., "Dynamic response and design of continuous concrete railway bridges in resonance area," *Doboku Gakkai Ronbunshu*, Vol. 724, pp. 83-102, 2003(in Japanese).
- [2] Nassif, H. H., Gindy, M. and Davis, J., "Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration," *Ndt & E International*, Vol. 38, No. 3, pp. 213-218, 2005.
- [3] Fujino, Y., "Vibration, control and monitoring of long-span bridges—recent research, developments and practice in Japan," *Journal of Constructional Steel Research*, Vol. 58, No. 1, pp. 71-97, 2002.
- [4] Somaschini, C., Matsuoka, K. and Collina, A., "Experimental analysis of a composite bridge under high-speed train passages," *Procedia engineering*, Vol. 199, pp. 3071-3076, 2017.
- [5] Sogabe, M., Matsumoto, N., Kanamori, M., Sato, T. and Wakui, H., "Impact factors of concrete girders coping with train speed-up," *Quarterly Report of RTRI*, Vol. 46, No. 1, pp. 46-52, 2005.
- [6] Sogabe, M., Furukawa, A., Shimomura, T., Iida, T., Matsumoto, N. and Wakui, H., "Deflection limits of structures for train speed-up," *Quarterly Report of RTRI*, Vol. 46, No. 2, pp. 130-136, 2005.
- [7] Kaneda, A. and Kobayashi, K., "A study on dynamic response of concrete bridges when a high speed train runs," *Proceedings of the Japan Concrete Institute*, Vol. 28, No. 2, pp. 31-36, 2006.
- [8] Ono, S., Numakura, A. and Odaka, T., "High-speed track inspection technologies," *JR East Technical Review*, No. 2, 2003.

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