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研究課題名（和文） Practicability study on drive-by methods for vibration-based bridge damage detection and modal identification

研究課題名（英文） Practicability study on drive-by methods for vibration-based bridge damage detection and modal identification

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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：本研究では、drive-by橋梁振動計測システムを開発することにより、drive-by橋梁異常検出とモード同定の実用性を示した。具体的な成果は下記の通りである。
1)drive-by手法向けの妥当な車両モデルを提案し、室内実験により検証した。2)フルスケールのトラクタ―トレーラー型のdrive-by計測システムを提案し、組み立てた。特に、トレーラーが自家製であり、車体の重量とサスペンションの剛性を調整することで、振動数をトラクタとした乗用車と共振しないようにより高い帯域に調整した。3)提案したdrive-by計測システムは、実鋼桁橋上でテストした。このシステムの特徴と制限は解明した。

研究成果の学術的意義や社会的意義
学術的に、本研究では1）振動に基づく橋梁異常検出とモード同定のためのdrive-by手法の実用性を示した；2）世界で最初のいくつかのフルスケールのdrive-by計測システムを提案・開発した；3）解析的および数値的研究で観察できなかった実際的な課題を示した。
さらに、本研究の成果は政府や産業に貢献することができる。Drive-by計測手法は低コスト、高機動性、高空間分解能などを特徴とするため、喫緊の課題である橋梁点検作業に役立つ。

研究成果の概要（英文）：This study mainly presented the practicability of drive-by methods for vibration-based bridge damage detection and modal identification by developing a practical drive-by vibration sensing system. Specifically, the following achievements were presented.
1) An appropriate laboratory-scale vehicle model was proposed for drive-by bridge inspections and tested on a scaled bridge model. 2) A real-life drive-by measurement system of tractor-trailer type was proposed and assembled. The focus herein is that the trailer was homemade, whose frequencies can be tuned to a higher range for avoiding close resonance with bridge vibrations by changing the body mass and the suspension stiffness, while the tractor was a commercial car. 3) The drive-by measurement system was tested in field on a 40-m steel girder bridge. Its main characteristics and limitations were presented.

研究分野：構造工学・地震工学・維持管理工学

キーワード：モード解析　損傷検知　橋梁振動　車両ー橋梁連成系　構造ダイナミクス　橋梁点検　車両応答　drive-by method

１．研究開始当初の背景

Bridge health monitoring (BHM) has become an important issue in bridge management and maintenance. Current BHM tasks heavily rely on visual inspections and conventional vibration-based methods that involve the deployment of vibration sensors on target bridges. Besides those, drive-by inspection methods that treat a moving vehicle as moving sensor were also attracting great attention. They utilize the vibrations of a test vehicle when the vehicle passes over the target bridge, and therefore have the advantage of low cost, high mobility, and high spatial resolution, and especially suit fast condition screenings. Since 2004 when the concept was proposed, it has drawn great attention worldwide, including famous researchers from UK, Ireland, USA, Taiwan, China, and more. Moreover, this new method has been suggested to many applications, including bridge dynamic-property extraction, damage detection, roadway roughness identification, and more.

Previous studies on drive-by methods were mostly based on analytical derivations and numerical simulations. Several laboratory-scale experiments were conducted but limited to feasibility study rather than thorough practicability study. Field trials were rarely presented. The small number of practically successful cases were mostly due to the limited understanding in vehicle-bridge interaction problems and limited experiment resources. No real inspection sensing system nor even a proposal presented at the current stage, leading its practicability to an open question.

２．研究の目的

This study aimed to present the practicability of drive-by methods for vibration-based bridge damage detection and modal identification by developing a practical drive-by vibration sensing system. This sensing system would label one of the first few stereotypes in the world and break through the bottleneck of this research field. Specifically, this study was devoted to 1) presenting a proper sensing system (hardware) that is sensitive to bridge vibrations and potential damage, 2) incorporating analysis methods (software) into the system for identifying bridge modal properties and detecting potential damage, 3) validating it in laboratory, 4) proposing and assembling a full-scale sensing system, and testing it in field.

３．研究の方法

This study was conducted in the following flow.

3.1. Presenting a proper sensing system (hardware)

An optimal vibration sensing system is definitely the key factor in successful drive-by methods for bridge modal identification and damage detection. It should be sensitive to bridges' vibrations and potential damage but insensitive to other unwanted vibration sources. This sensing system were assembled as a vehicle structure equipped with vibration sensing modules (Figure 1(a)). Through (1) numerical simulations using our in-house vehicle-bridge interaction dynamic analysis program and (2) laboratory-scale experiments using our assembly vehicle and scaled model bridge (Figure 1(b)), all the following components were designed and optimized per our findings given in Section 4.1.

1) Vehicle structure

According to our previous studies, the tractor-trailer type would be a proper vehicle structure. The tractor serves as the bridge vibration exciter and the trailer serves as the bridge vibration receiver (equipped with sensors).

2) Dynamic properties of the vehicle structure and their criteria

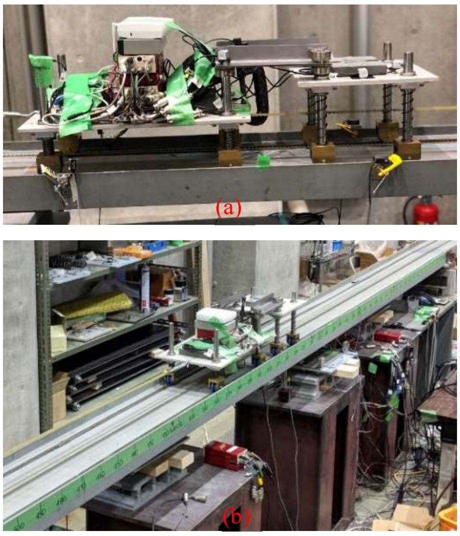

Figure 1. Laboratory-scale experiments:
(a) tractor-trailer type drive-by sensing system;
(b) model vehicle and bridge

The vehicle structure serves as a sensing platform. Its dynamic properties are the key factor to the successful sensing of bridge-related vibrations. With our knowledge in vehicle-bridge interaction problems, we were devoted to finding out the theoretically optimal dynamic properties and criteria, including but not limited to the following.

- Number and type of dominant modes: An intuitive choice would be a trailer having solely a single bouncing mode, i.e. having a single axle. However, the single-degree-of-freedom (degree of freedom denoted by DOF afterwards) structure is unstable in reality. To keep its balance, proper connections between the trailer and its adjacent tractor or trailer was required. In the laboratory, the balance of the single-DOF structure was hardly kept, so a two-DOF trailer (i.e. a two-axle trailer) would be alternatives although multiple modes would present and complicate the vehicle responses. In the field, the full-scale vehicle structure was designed and assembled as close as possible to a single-DOF structure.
- Frequency bands: The frequency bands of the vehicle structure should be well tuned. Locating too close to the target bridge frequencies (generally 1 to 5 Hz) would

confuse the identification; too far from the bridge frequencies would be unrealistic. A tradeoff was unavoidable.

- Connectors: The connectors between tractor and trailer would be an important factor that dominate the vehicle structural modes. Whether they constrain certain vehicle modes or introduce new ones should be clarified.

3) Layout of sensors and other devices

- Sensors: In previous studies, accelerometers were the majority for its low cost and high availability. They remained the main sensor type, and less noisy ones were used.
- Mass block: The installation of mass block was closely related to the vehicle dynamic properties (Item 2). In this study, it was used to tune the trailer's frequency and to increase the tractor's weight for amplifying target bridge's vibrations.
- Layout: The optimal type and layout of those sensors and devices was investigated.

3.2. Designing and assembling a laboratory-scale sensing system

Laboratory-scale sensing system model was designed and assembled with the components meeting the proposed criteria. Specific components include the vehicle structure's main body, wheels, suspension springs, connectors between the tractor and trailer, sensing modulus, cables, etc.

3.3. Developing and validating incorporated analysis methods (software)

We have developed several analysis methods for identifying bridge modal properties and detecting potential damage from the moving vehicles' vibrations. Those analysis methods were incorporated into the laboratory-scale sensing system and validated with our scaled bridge model. Current challenges are the too large roadway roughness-induced vibrations and the too small bridge-induced vibrations. Its solutions or improvements were proposed in both hardware (Item 3.1) and software ways (Item 3.3) and tested repeatedly in laboratory. Specifically, the following analysis methods were developed. Relevant findings are given in Section 4.3 and 4.4.

- To reduce or eliminate the adverse effect of roadway surface profile roughness on the vehicle responses using two identical trailers.
- To improve the accuracy of road profile identification from the test vehicle responses by correcting the inclinations of sensors on the vehicle.
- To improve the accuracy of road profile identification from the test vehicle responses by an a priori, self-adaptive and straightforward method using a complementary pair of vehicle models, one with and the other without un-sprung mass.

3.4. Proposing and assembling a prototype full-scale sensing system and testing it in field

A prototype full-scale sensing system was proposed as per the feedback from the laboratory experiments. Our intuitive idea was to take a commercially available vehicle as the trailer and to assemble a trailer that serves as the sensing platform equipped with vibration sensors. The trailer was therefore a key element, which should reflect the above findings and satisfy the above principles and criteria. The scale effects were carefully considered between laboratory- and full-scale systems. Such a full-scale drive-by sensing system was assembled and tested on a steel girder bridge in field. Relevant findings are given in Section 4.2.

４．研究成果

The research achievements can be briefly summarized as follows.

4.1. Working out an appropriate vehicle model for drive-by bridge inspection methods through a laboratory experimental study

We worked on the tractor-trailer model and worked out an appropriate tractor and trailer model among several candidates based on their transmission performance in free vibration tests. To quantify the transmission performance, two indices were introduced: one was a frequency accuracy index, quantifying how accurate the target bridge frequency was identified from the vehicle vibrations, and the other was a visibility index, quantifying how easy the target bridge frequency could be identified from the vehicle's power spectral density. It was found that he appropriate tractor-trailer system was characterized by a tractor having the heaviest weight and a trailer having the highest bouncing frequency. The heavy tractor was to excite the bridge easily. The trailer of high frequency was shown to transmit bridge's

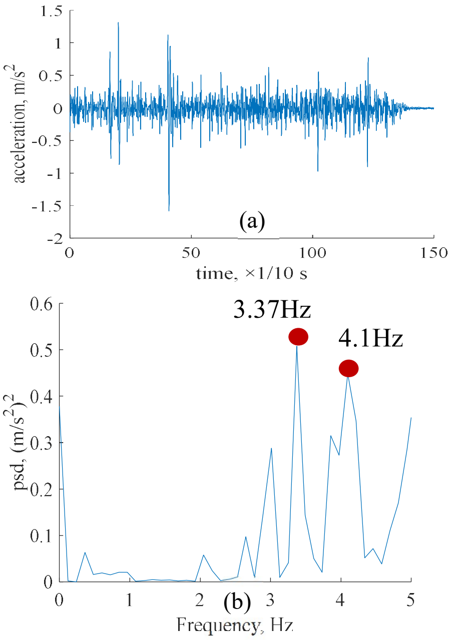

Figure 2. Typical Acceleration response of the trailer moving on the scaled bridge: (a) time history; (b) power spectral density

vibration energy better, and therefore made the bridge dynamic properties more identifiable; moreover, it identified the bridge frequency as accurately as the other trailer did of lower and closer frequency band to the target bridge's.

Selecting a trailer of high bouncing frequency can be justified by the following empirical considerations: 1) to avoid the close resonance between vehicle frequency (usually of the bouncing mode) and the target bridge frequencies; 2) to avoid the frequency variation caused by the vehicle-bridge interaction; 3) to reduce the negative impact of roadway surface roughness.

The performance of this tractor-trailer system to identify bridge dynamic properties was verified in laboratory moving vehicle tests. In slower speed cases, the bridge-related frequencies were obviously identified from the trailer's power spectral density. Figure 2 shows a typical acceleration time history and power spectral density of the trailer moving on the model bridge with speed 0.55 m/s, from which the bridge relevant frequencies are observed at 3.37 Hz and 4.1 Hz. However, in higher speed cases, several peaks irrelevant to bridge frequencies presented due to the negative effect of roadway profiles. Despite that, the indices and criteria presented herein would be helpful in designing and assembling a real tractor-trailer-type drive-by inspection system in practice.

4.2. Proposing and assembling a prototype full-scale sensing system and testing it in field

We proposed and assembled a prototype full-scale sensing system and tested it in field. Following our findings from the laboratory experiments, the sensing system herein was again of tractor-trailer type: the tractor served to excite the target bridge and the trailer served to capture the target bridge vibrations. The focus herein is that the trailer was homemade, whose frequencies could be tuned by changing the body mass and the suspension stiffness, while the tractor was a commercial car.

The trailer was a simple uni-axle two-wheeled structure (see Figure 3). It firmly connected to the tractor in order to suppress the pitching mode vibrations. The trailer was made of aluminum, and its mass was 14 kg. The length was 860 mm, the width was 600 mm, and the height was 305 mm. The body was supported by two tires. The tires were made of natural rubber and the mass was 2.2 kg. The wheel diameter was 285 mm and the width of rim was 90 mm. The trailer's bouncing frequency was empirically tuned to a frequency band higher than general bridge frequencies (usually 2~4 Hz for the first bending mode), for the purpose of avoiding resonances with target bridge frequencies and of reducing the road surface roughness' negative effects. This could be beneficial to the extraction of bridge characteristics. In the pre-test, free vibration tests and moving vehicle tests on plane roads were conducted. From these tests, it was observed that the trailer's bouncing frequencies were about 8 Hz when it is stationary and about 9 Hz when moving.

Figure 3. Assembled trailer

Figure 4. Field test bridge

In the field test on a steel girder bridge (Figure 4), the fundamental bridge frequencies were successfully identified from the trailer's responses in most runs and the identified bridge frequencies were very close to the ones identified by conventional methods. Figure 5 shows a typical acceleration time history and power spectral density of the assembled trailer moving on the field test bridge with a speed of 10 km/h. A clear peak presented around 3 Hz, which is identified as bridge bending frequency with acceptable accuracy. The practicability and accuracy of the drive-by method using the homemade trailer could be preliminarily verified.

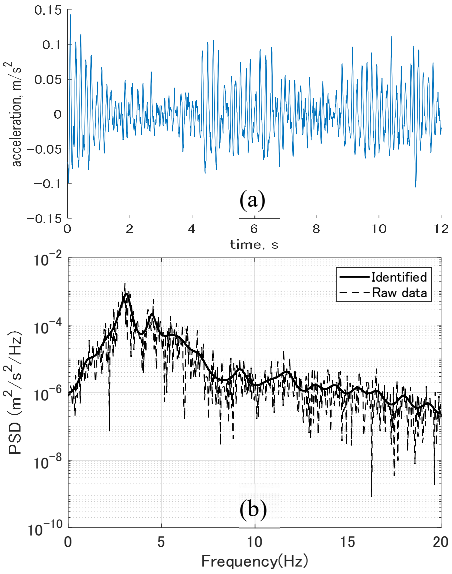

Figure 5. Acceleration response of the trailer moving on the test bridge with speed 10 km/h: (a) time history; (b) power spectral density

4.3. Improving the accuracy of road profile identification from the vehicle responses by correcting the inclinations of sensors on the vehicle

To improve the accuracy of road profile identification by drive-by inspection method, we devoted to correcting the inclination of sensors installed on the test vehicle. Through a study on the synthetic signals and the observations in a field experiment on a steel girder bridge, we proposed and validated an updated method for road profile identification considering sensor inclination corrections. First, for all runs, calculate the correlation coefficient R between x and z accelerations (denoted as $\ddot{x}$ and $\ddot{z}$ respectively) and the ratio of their standard deviation, $\sigma_{\ddot{x}}/\sigma_{\ddot{z}}$. Decide a threshold R_{th} by taking the largest R when $\sigma_{\ddot{x}}/\sigma_{\ddot{z}} < 1$. Then, if $R > R_{\text{th}}$, correct the initial inclination by an existing method: fitting a linear regression line from the $\ddot{x}$-$\ddot{z}$ plots by least-squares method, and taking the slope of the linear regression line as tangent of the sensor's initial inclination angle; if $R < R_{\text{th}}$, no need to correct the sensor's initial inclination. The correction is done separately for front and rear sensors. Second, calculate instantaneous inclinations by integrating the instantaneous angular velocities measured from a gyroscope and then correct the instantaneous inclinations. Then, input the corrected vehicle accelerations to the existing road profile identification algorithm to identify road profiles.

The present sensor inclination correction method was validated in field. Figure 6 shows a typical surface profile identified with the present method and compared with exact profile as well as that identified with the past method (with no sensor inclination correction). It is observed that there were downward and upward trends in the road profile identified by the past method, and that the trends were clearly removed by the present method. This observation demonstrated a better performance of the present updated road profile identification incorporating sensor inclination corrections.

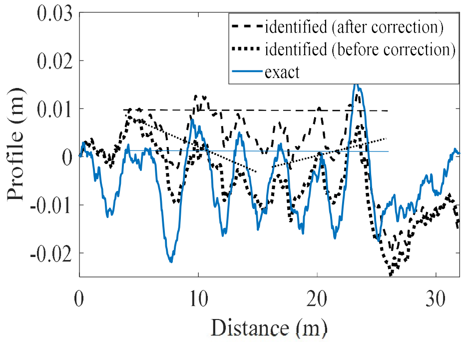

Figure 6. An example presenting updated method for road profile identification

4.4. Improving the accuracy of road profile identification by an a priori, self-adaptive and straightforward method using a complementary pair of vehicle models

To improve the accuracy of road profile identification from the test vehicle responses, we proposed an a priori, self-adaptive and straightforward method using a complementary pair of vehicle models, one with and the other without un-sprung mass. The present method was rooted from a numerical study on how the following four numerical vehicle models affected the accuracy of road profile identification using drive-by bridge inspection: 1DOF and 2DOF quarter-car (the former without and the latter with un-sprung mass) and 2DOF and 4DOF half-car models (the former without and the latter with un-sprung mass). It was shown that the vehicle models without un-sprung mass were more capable of identifying profiles in lower frequency bands accurately while those with un-sprung mass were more capable of identifying profiles in higher frequency bands. The present method works as follows.

1) Select a complementary pair of vehicle models, which could be 1DOF and 2DOF quarter-car models or 2DOF and 4DOF half-car models
2) Quantitatively find out in which frequency band each vehicle model was capable of identifying the road profile more accurate than the other using a series of sinusoidal profiles.
3) Identify road profiles using two models respectively, and then extract road profile components in the corresponding frequency bands from the respective road profile identified by both vehicle models.
4) Assemble the two extracted profile components into one. The resultant profile was taken as the final outcome of the roadway profile.

For one typical example, when a 1DOF quarter-car model (without un-sprung mass) was used to identify a target road profile, it could identify low frequency components well but high frequency components fairly (Figure 7(a)). On the other hand, when a 2DOF quarter-car model (with un-sprung mass) was used, it could identify high frequency components well but low frequency components fairly (Figure 7(b)). When the present method was used that taking the respective advantage of the complementary pair of 1DOF or 2DOF models, it could identify the road profile better than the 1DOF and 2DOF model could (Figure 7(c)).

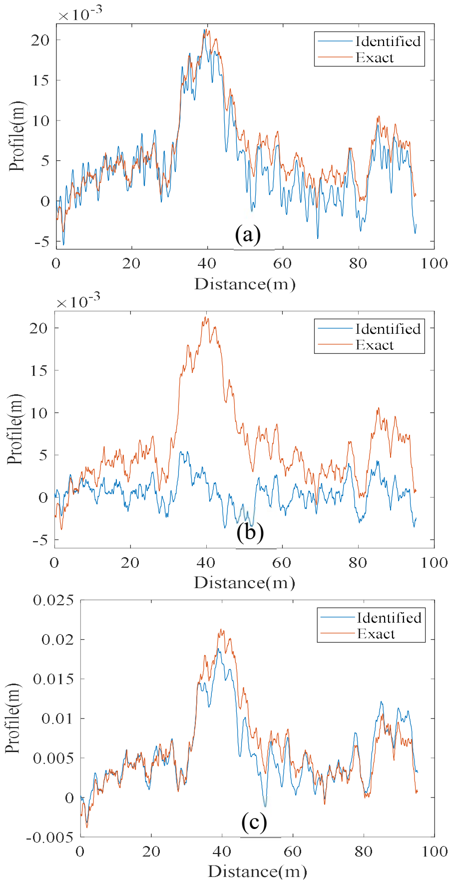

Figure 7. Road profiles identified by (a) 1DOF quarter-car model; (b) 2DOF quarter-car model; (c) the present method

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　3件／うちオープンアクセス　2件）

１．著者名 Chang Kai-Chun, Kim Chul-Woo, Hasegawa Souichiro,Nakajima Shunsuke, McGetrick Patrick J.	４．巻 3
２．論文標題 Estimation of bridge surface profile from moving vehicle accelerations by means of moving force identification - an experimental field study	５．発行年 2019年
３．雑誌名 International Journal of Lifecycle Performance Engineering	６．最初と最後の頁 289～309
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1504/IJLCPE.2019.103698	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Huseynov F., Kim C., OBrien E.J., Brownjohn J.M.W., Hester D., Chang K.C.	４．巻 135
２．論文標題 Bridge damage detection using rotation measurements - Experimental validation	５．発行年 2020年
３．雑誌名 Mechanical Systems and Signal Processing	６．最初と最後の頁 106380～106380
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1016/j.ymssp.2019.106380	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Chul-Woo Kim, Kai-Chun Chang, Patrick J. McGetrick, Shinichi Inoue and Souichiro Hasegawa	４．巻 29
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掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.18494/SAM.2017.1433	査読の有無 有
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１．著者名 C.W. Kim, K.C. Chang, Y. Sasaka, Y. Suzuki	４．巻 188
２．論文標題 A Feasibility Study on Crack Identification Utilizing Images Taken from Camera Mounted on a Mobile Robot	５．発行年 2017年
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掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1016/j.proeng.2017.04.456	査読の有無 有
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2．発表標題
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３．学会等名 The 30th KKHTCNN Symposium on Civil Engineering
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１．発表者名 中嶌俊祐,金哲佑,張凱淳,長谷川聡一朗
２．発表標題 走行車両による橋梁振動数同定に適した車両モデルの検討
３．学会等名 土木学会関西支部年次学術講演会
４．発表年 2017年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
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研究協力者	マゲトリック　パトリック・ジョン (McGetrick Patrick John)	アイルランド国立大学ゴールウェイ	