INDIRECT MEASUREMENT OF BRIDGE FREQUENCIES BY A HAND-DRAWN CART

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ABSTRACT

The technique presented is an *indirect approach* for measuring the bridge frequencies, using the vibration sensor mounted on a hand-drawn cart, rather than on the bridge. With this technique, the bridge frequencies can be measured in a rather efficient and mobile way. The dynamic properties of a test vehicle are crucial to successful identification of the frequencies of the bridge traveled by the vehicle. In this study, focus is placed on the elastic properties of the cart wheels and the reliability of bridge frequencies extracted from the test cart. Various tests are conducted for various purposes, including the ambient vibration test, free vibration test, ground dynamic test, and field test. It is demonstrated that the hand-drawn cart presented herein can be reliably used in the field for measuring the bridge frequencies. Furthermore, some *qualitative guidelines* that are crucial to the development of feasible test vehicles are drawn from the test studies presented herein.

Keywords: Bridge, field test, frequency, measurement, tire, vehicle, vehicle-bridge interaction.

1. INTRODUCTION

The frequencies of a bridge are among the most important information for health monitoring, as they relate closely to the stiffness or loading capacity of the bridge. A drop in any frequency of the bridge implies some deterioration in the stiffness of the structure, possibly caused by damages in certain components or supports of the structure. Conventionally, the frequencies of a bridge are measured by mounting a number of sensors on the bridge, referred to as the direct approach. Such an approach can be reliably used to obtain the dynamic properties of the bridge. However, it suffers from the drawback of being costly, inefficient, and not qualified for emergency use, say, for monitoring a large number of bridges after a major natural hazard.

To this end, an *indirect approach* was proposed by Yang et al. (2004) and Lin and Yang (2005) by analyzing the dynamic response of a test vehicle recorded during its passage over a bridge to extract the frequencies of the bridge. Theoretically, the moving vehicle plays the dual role of an exciter to the bridge and also of a message receiver of the bridge. As far as the bridge frequency measurement

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is concerned, the indirect approach is superior to the direct ones in terms of mobility, since the vibration sensors need only to be installed on the test vehicle, rather than on the bridge. In this study, a hand-drawn cart will be adopted to measure the bridge frequencies, with focus placed on the dynamic properties of the cart using different wheels. Various tests will be conducted, including the ambient vibration test, free vibration test, surface dynamic test, and field test, to verify the applicability of the proposed cart. Finally, some conclusions will be drawn.

2. DYNAMIC PROPERTIES OF HAND-DRAWN CART

The hand-drawn cart used is made by thin-walled stainless steel bars with replaceable wheels. The key idea is to let it behave like a single-degree-of-freedom system similar to the one theoretically studied in Yang et al. (2004). As shown in Fig. 1, the cart is composed of a steel frame with weight = 42 kg, width = 65 cm, height = 20 cm. Besides, steel plates can be mounted under the frame to serve as added weight. Three deferent types of wheels are used: inflatable wheels, rubber wheels, and PU wheels, shown in Fig. 2. All details of these tires are given in Yang et al. (2013b).

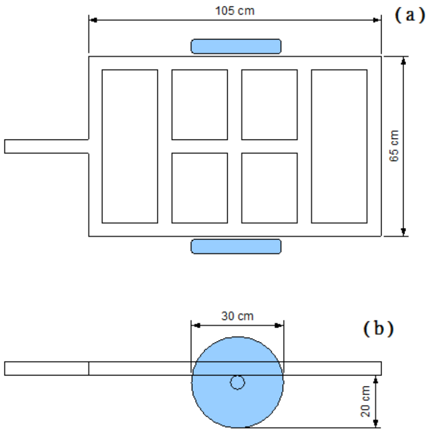

Fig. 1: Hand-drawn cart.

3. BASIC DYNAMIC TESTS

The natural frequency of the cart is the key parameter that determines the transmission of energy from the bridge to the cart. For better visibility of the bridge frequencies from the cart response, it is preferable that the cart frequency be made larger than the first frequency of the bridge (Yang et al. 2013a). In this study, three kinds of dynamic tests, i.e., the ambient vibration test, free vibration test, and surface dynamic test, will be conducted using the three types of wheels shown in Fig. 3.

To conduct the *ambient vibration test*, an accelerometer is mounted at the center point of the axle to record the vertical acceleration of the cart installed with different wheels. The time-history responses recorded for three types of wheels have been presented in frequency domain by fast Fourier transform (FFT) in Fig. 3. Clearly, no particular peaks are observed from the responses for the case with rubber wheels and PU wheels. However, a resonant peak (natural frequency) exists for the case with inflatable wheels in the 16 - 17 Hz range. This implies that the cart with inflatable wheels can be more easily excited than

Fig. 2: Wheels: (a) inflatable, (b) rubber, (c) PU.

the other two wheels under tambient vibrations. Thus, inflatable wheels are not considered a favorable choice.

In the *free vibration test*, the vertical acceleration response of the cart is recorded when subjected to an impulse force, generated by the sudden jump of a person from the cart to the ground. From the FFT responses obtained for the three types of wheels (Yang et al. 2013b), it is observed that there exists a single obvious peak at about 15 Hz for the car with inflatable wheels. However, no such clear peaks exist for the other two types of wheels. In particular, the cart with PU wheels shows a most favorable dynamic property in that it has no natural frequencies in the range 0 - 50 Hz, which should prove that it is more suitable for use in the bridge measurement.

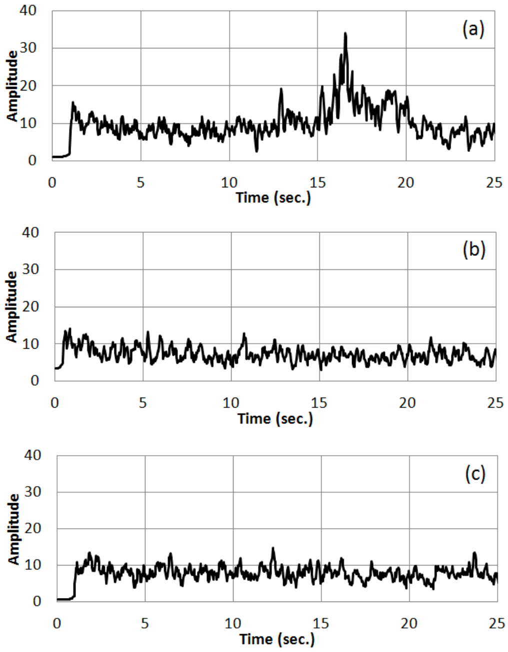

Fig. 3: Ambient vibration test: (a) inflatable, (b) rubber, (c) PU.

To identify the dynamic properties of the test cart under moving conditions, *ground dynamic tests* are conducted by letting the cart slowly pulled over a smooth concrete pavement at a speed of about 2 m/s. The time-history responses recorded for the three types of wheels have been processed by FFT and plotted in Fig. 4. Clearly, the cart with inflatable wheels has a natural frequency peak at about 13 Hz, while the cart with rubber wheels shows concentrated frequency peaks in the 30 to 35 Hz range. In contrast, the spectral content of the cart with PU wheels, as shown in Fig. 4(c), shows only a random, small and even distribution of amplitudes throughout the range of frequencies of concern, i.e., 0-50 Hz, for which no natural frequencies are observed for the cart. As a result, when using the PU wheels, the cart response can *faithfully* reflect the smooth concrete pavement, of which the roughness profile is similar to the *white-noise random distribution*. For this reason, PU wheels are selected for further field tests for their relatively good performance in the later part of study.

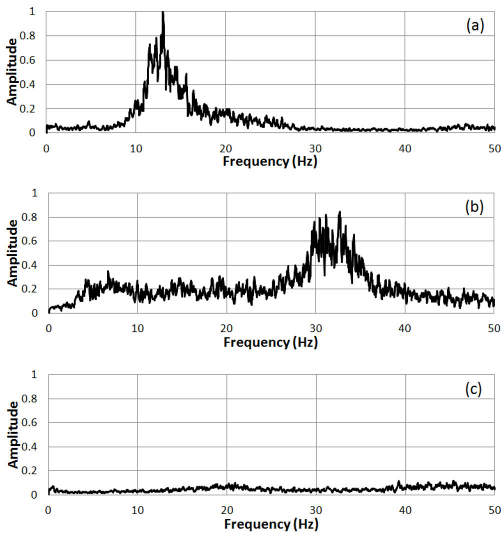

Fig. 4: Ground vibration test: (a) inflatable, (b) rubber, (c) PU.

4. FIELD TESTS

The objective herein is to search for a better configuration of the test cart, concerning the weight and speed of the cart and existing traffic flows, such that it can be successfully used to extract the bridge frequencies. To this end, the Stochastic Subspace Identification (SSI) method will be adopted to identify the natural frequency peaks of the bridge of concern. It is an output only signal identification technique, collocated with the household of FFT (Peeters and de Roeck 1999).

Effect of cart weight: The first bridge to be measured is the Ping-Pu Bridge of 95 m span located in the suburb of the Taipei City (Yang et al. 2013b). The cart is pulled over the bridge with two different weights, 94 and 146 kg, at the speed of 2 km/hr. The sampling rate for recording the data of vertical acceleration is 200 Hz.

From the time-history responses recorded for the cart during its passage over the bridge for the two weights, not shown herein, it is concluded that *the higher the cart weight, the smaller the cart response* (Yang et al. 2013b). This means that a heavier cart is relatively insensitive to the road surface roughness and should be adopted in the field measurement.

The FFT/SSI results obtained for the response of the cart with the two weights have been presented in Fig. 5. Clearly, *a heavier cart can extract many more bridge frequencies than a lighter cart*, due to the fact that the pollution effect of road surface roughness has been largely suppressed by the cart weight. For instance, for the cart with 94 kg, one observes from Fig. 5(a) that only the 2nd and 5th frequencies of the bridge are identified. But for the cart with 146 kg, all the frequencies of the bridge from the 2nd to the 8th can be identified from Fig. 5(b).

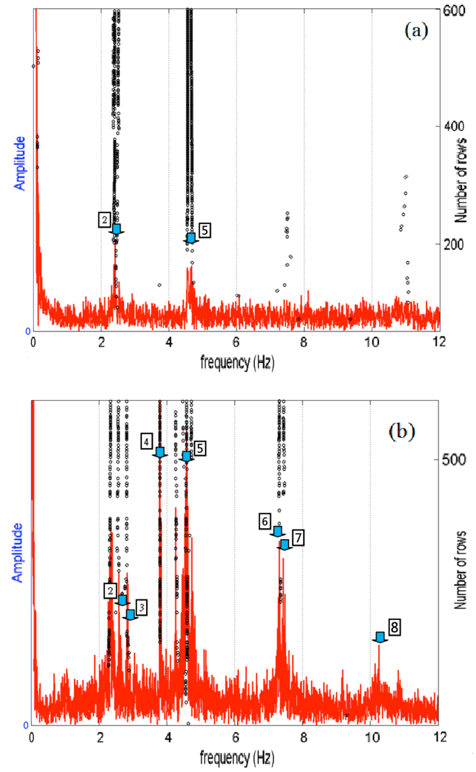

Fig. 5: Ping-Pu Bridge test: (a) 94 kg, (b) 146 kg.

Effect of various cart speeds: For efficiency, one would prefer a test cart pulled at a speed as high as possible. There are two concerns herein, however. First, a higher moving speed means that the *contact time* of the cart wheels with the bridge surface is short, thereby reducing the effectiveness of energy transmission from the bridge to the cart. Second, a cart moving at higher speeds is less stable, in that it can be more easily excited by the road surface roughness. To evaluate how the moving speed of the cart affects the measured response, three testing speeds are considered: 2, 4, and 8 km/hr. The bridge tested is the Jie-Shou Bridge of 84 m span, also located in the suburb of the Taipei City (Yang et al. 2013b).

An impression from the recorded responses of the cart, not shown here, is that higher travelling speed will induce larger vibrations, coupled with higher roughness amplification. This is not good for bridge frequency identification. The FFT/SSI frequency responses for the 2 and 8 km/hr speeds were plotted in Fig. 6(a)-(b). For the 2 km/hr case, six bridge frequencies are identified. However, only four bridge frequencies are identified for the 4 km/hr speed (not shown). Even worse, when the speed increases to 8 km/hr, basically no bridge frequencies can be identified (see Fig. 6(b)). As mentioned previously, for a cart moving at higher speeds, the contact time between the cart and bridge will be reduced, while the pollution effect of road surface roughness will be amplified. Both factors are not good for bridge frequency identification.

Various Volumes of Existing Traffic Flows: An experiment has been designed to test the relationship between the identifiability of bridge frequencies and the volume of existing random traffic flows on the bridge. Two different existing traffic flows are considered for the Shi-Lin Bridge (Yang et al. 2013b).

The FFT/SSI responses obtained for the cart with large and small traffic volumes were plotted in Figs. 7(a) and (b). Here the terms of large or small volumes of traffic flows represent only a qualitative, not very rigorous, description of the number of vehicles moving over the bridge at the time of testing. To give some feeling, a large volume of traffic flow refers to the case where there is a continuous flow of vehicles moving at rather high speeds, say, over 50 km/hr. The reverse is true for the small volume of traffic.

As can be seen, for the *large volume* case, virtually *all the first five frequencies* of the bridge can be identified. However, for the small volume case, only the first, fourth, and the fifth frequencies of the bridge can be roughly identified, i.e., at a lesser degree of visibility. It should be realized that for a complicated bridge such as the Shi-Lin Bridge (i.e., a four-span continuous beam) and for a cart moving at the speed of 4 km/hr (which was considered unfavorable in the previous test of the Jie-Shou Bridge), such a result is very encouraging. Evidently, the identifiability of bridge frequencies can be greatly enhanced by the existing traffic, which is *available* in almost all bridges. Further, the higher the volume of the existing traffic is, the better the resolution can be achieved.

This test confirmed that the vibration energy transmitted by the existing traffic onto the bridge is helpful to identification of the bridge frequencies from the dynamic response of the moving cart, in consistence with the previous finding on such an effect (Lin and Yang 2005).

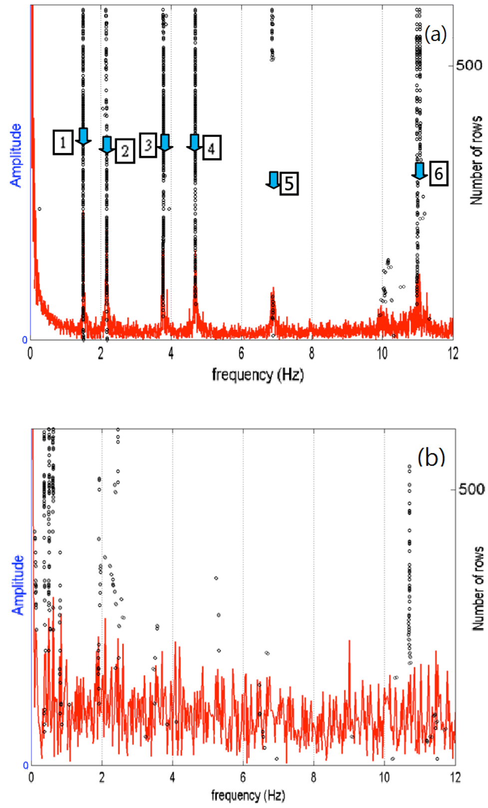

Fig. 6: Jie-Shou Bridge test: (a) 92 km/hr, (b) 8 km/hr.

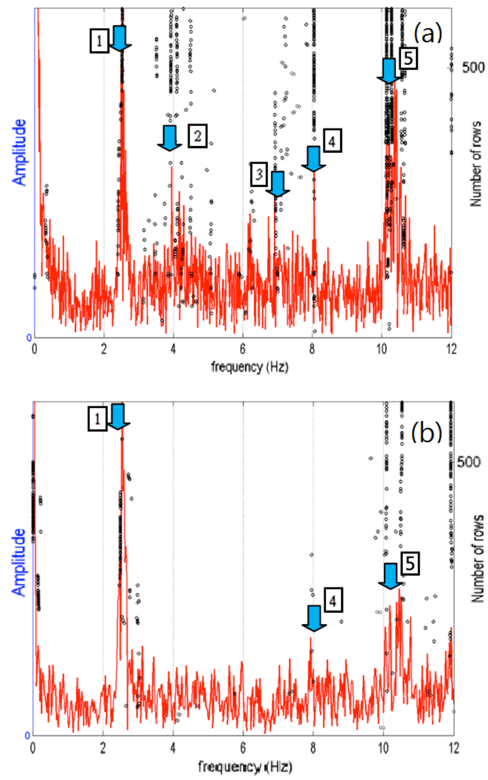

Fig. 7: Shi-Lin Bridge test: (a) large traffic, (b) small traffic.

5. CONCLUSIONS

The following conclusions are made for the various tests conducted using the hand-drawn cart:

- The PU wheels appear to be the most suitable, among the three types of wheels tested, for use in the indirect approach for extracting the bridge frequencies, since it shows no particular self frequencies in the range of frequencies of interest.
- Higher moving speeds for the test cart will bring in extra, amplified interference from the road surface roughness, thereby making it difficult to identify the bridge frequencies.
- *The heavier the test cart is, the smaller the cart response, and the higher the visibility can be achieved for the bridge frequencies*.
- *Larger volumes of existing traffic flows tend to make the bridge frequencies more visible as measured from the moving cart response*, which is beneficial to the field measurement as the traffic flows are available on all bridges.

This study confirms that the test cart is a handy, feasible device for measuring bridge frequencies. The conclusions drawn herein, mainly qualitative in nature, are helpful to the design of test cart of the second generation. Further studies will be conducted along these lines to improve the structure of the test cart such it can be pulled by a tractor at higher speeds in the field.

6. ACKNOWLEDGMENTS

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