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Vibrational analysis of the benchmark data set

Douglas Thomson[1]
[1]Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6, Canada
email: Douglas.Thomson@umanitoba.ca

ABSTRACT: Traffic induced vibration is a promising means of continuously monitoring structural behavior. The benchmark data set measures strain at points that will be subject to traffic induced vibration. However, magnitude and frequency spectrum of the induced vibration from an individual vehicle depends on many factors including the vehicle speed and axle weight distribution. Therefore, to obtain a spectrum that is representative the average vehicle induced vibration the vibration from many vehicles must be examined. In this work several methods for the analysis of the strain versus time data to extract traffic induced vibrational spectrums will be compared. Also, the number of vehicles that need to be analyzed to extract a repeatable vibrational spectrum will be examined. Typically, ~40-50 vehicles are needed to obtain a repeatable vibrational spectrum suitable to extract frequency peaks. This approach is used on the benchmark data set and changes in the vibration frequencies due to temperature induced structural changes can easily be observed. The temperature induced structural changes might be the basis training and testing data sets that could be used to evaluate the effectiveness of some damage detection algorithms.

KEY WORDS: SHMII-13; benchmark data, vibrational analysis, training data

1 INTRODUCTION

Structural vibrational analysis of bridges has been used for many purposes including structural assessment [1], damage detection [2], cable damping [2], damage detection in piers [3], girders [4], bearing restraint [5] and scour detection [6], [7], [8]. Vibrational analysis via moving test vehicles is also an exciting direction [9]. Vibrational analysis can be extracted from specialized instruments such as accelerometers and geophones, but can also be extracted from strain signals from strain gauges or strain sensors [10].

Some type of force must be applied to the structure in order to detect vibration of the structure. The excitation can be broadly classified as intentional or unintentional excitation. Intentional excitation can be in the form of hammers, dropped load, unbalance rotating shaft or known test vehicles. Unintentional excitation can be due to wind, water, ice impact or traffic. One advantage of unintentional sources is that they can excite the structure more or less constantly and allow for the continuous monitoring of the bridge. In this context, continuous means a time scale on the order of a fraction of a day. We can use the data from the benchmark data set to explore the sue of traffic induced vibration to extract vibrational information.

In this paper we examine the extraction of vibrational information from the benchmark data set. We examine alternative methods for the extraction of vibrational information from the strain versus time data in the benchmark data set. We examine the number of truck passages that are required to obtain a usable estimate of the vibrational frequencies of this bridge span. Suggestions for future vibrational analysis of this data set will also be given.

2 METHODS

2.1 Sampling strain versus time

The data being used is the individual truck sampled strain versus time data from the benchmark data set [11]. This publication contains the details of where the sensors were located and how the signals were sampled [11]. Briefly, the instrumentation was originally aimed to estimate the GVW of vehicles, investigate the transverse loading and to investigate the composite action in the structure. The span has two lanes and is 22 m long with 4 steel girders. An image of a truck passing over the girder is shown in Fig. 1.

Figure 1. Truck passing over the benchmark span.

The instrumentation included 32 electric resistive strain gages to monitor strains and six thermocouples to monitor air/structure temperature under the deck. The bridge was instrumented at six cross-sections.

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The cross-section used in this work is the one located at midspan and has electrical resistance strain gauges (ESGs) were installed on the web of each girder to measure longitudinal strains at the top and bottom flanges, and at mid-height between the flanges. In this work only the strains near the bottom flange are used.

The data acquisition (DAQ) system features continuous strain sampling at 200 Hz, image collection for large events, data processing, and data transmission to a server. The strain data were filtered using a 7-point moving average window to remove electrical noise above 60 Hz.

The benchmark data set contains subsamples of the full data set. Each subsample was selected to contain the sampled strain versus time for a large truck. Each subsample contained 2000 sample points or about 10 seconds of sampled data. The data was selected such that the peak strain for the passing vehicle was in the center of the subsampled data.

An example of the sampled strain versus time is shown in Fig. 2A. In this plot the strains from each girder are offset by 20 micros train per sensors so that the strain versus time behavior of each sensor can be easily observed. Before the passing of the vehicle there is no observable vibration. During and after the passage of the truck the vibration is clearly visible. After the truck leaves the span, during the period of free vibration without the weight of the truck, there are about 5 cycles per second [12]. This can be observed in the top strain versus time curve starting at about 6 seconds. Between 6 and 7 seconds there are about vibrational 5 cycles.

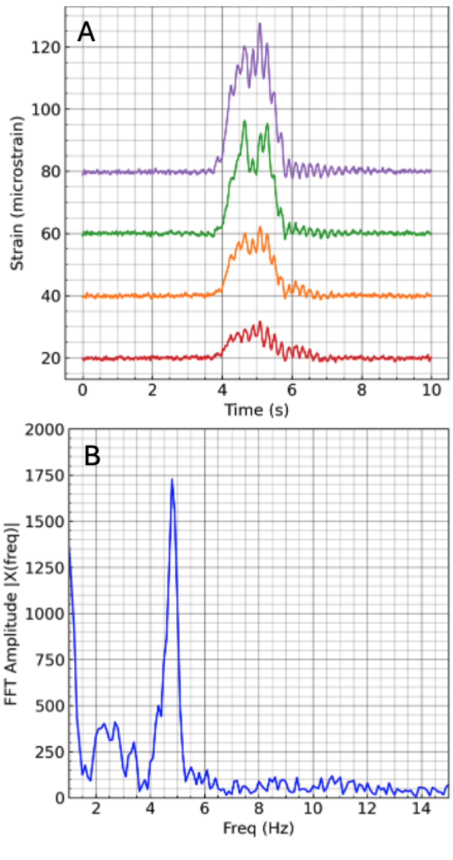

Figure 1. (A) Strains versus time for each of the 4 girders. (B) Spectrum of the strain. There is a vibrational peak at ~5Hz.

The strain versus time signals from the two outside girders were summed and then processed using an FFT from the Python numpy library. By using signals from the outside girders, vibration from trucks passing in both directions are captured. The outcome of the FFT analysis of Fig. 2A is shown in Fig. 2B. As expected, there is peak in the spectrum near 5 Hz. However, there is also considerable noise in the spectrum and the estimate of the peak position would have significant uncertainty. We will examine using averages of many such spectrums to improve the estimates of the vibrational frequency peaks. To do this N spectrums are averaged using a simple linear average. Using these initial estimates, a better estimate of the peak frequency was obtained by using a parabolic fit using two points lower and two points higher and the initial estimate. The peak of the parabola was then used as a refined estimate of the peak frequency. This means of estimating the peak position is computationally simple and produces a better estimate of the peak [13].

3 RESULTS AND DISCUSSION

There are several reasons why it may be necessary to use the average of vibrational spectrums from several trucks to obtain usable estimates of vibrational frequencies. When each truck passes it will preferentially induce vibration at certain frequencies. The frequencies that are preferentially excited will depend on factors like the velocity of the truck, the distance between axles, where the truck passes over the bridge and the vibrational properties of the truck.

An example of the variation in excited vibration is shown in Fig. 3(A) and 3(B). The two examples are passing at similar velocities with similar maximum strains. Both are traveling in the same direction. However, the induced vibration is not similar. In Fig. 3(A) during free vibration portion after the vehicle has left the span the vibration is largest on the side opposite the side on which the truck passed, in girder G4. After leaving the span the vibration on the girder nearest where the truck passed (G1), is much smaller and not observable. In contrast to this the in Fig. 3(B) the after the truck has passed and the girder is in the free vibration portion of the vibration the magnitude of vibration is roughly about the same in G1 and G4.

In Fig. 3(A) the vibration is torsional with one side moving and the other side nearly motionless. In Fig. 3(B) the vibration is more flexural with both sides moving up and down synchronously. The synchronous motion can be seen in Fig. 3(B) at 7 seconds where the strains in all the girders are at a maximum. In this example, for two similar trucks the mode of vibration is very different. It should be mentioned that these two examples were found within the first few trucks in the data set and did not require any extensive searching. Therefore, in general the vibration from a single truck may not excite all the modes of interest.

Using the benchmark data set, we can explore how many spectrums need to be considered by using stacked spectrum plots of the averaged spectrums. In these examples a simple linear average of spectrums is used. The numbers explored ranged from 40 to 200 spectrums. When less than 40 were used the number of misidentified vibrational peaks increased significantly. In Fig. 4(A) a stacked spectrum plot for an average of 200 spectrums is shown. In this plot each spectrum

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is an average derived from 200 truck passages. Each peak is identified with a black plus sign. With 200 spectrums being averaged there are no misidentified peaks. For each spectrum there is a peak near 5 Hz and a second one from 10 to 12 Hz. The 10 to 12 Hz peak appears to be shifting from the averaged spectrum at the bottom to the averaged spectrum at the top.

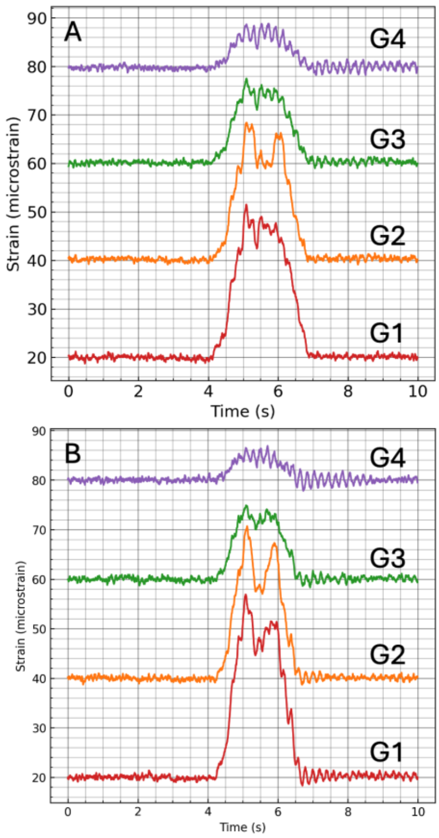

Figure 3. Strains versus time for the four girders. Fig. 3A is an example of asymmetric vibration. Fig. 3B is an example of symmetric vibration.

Each truck in the data set has a unique number from 0 to ~ 3300. As the truck number increases so does the date on which the data was acquired. Truck 0 was taken during a mid-winter cold period. By the time truck 3300 was taken it was mid-summer. The spectrums are arranged sequentially in number and therefore time. The bottom spectrum was from a colder period and the top one from a warmer period. The shift in frequencies is attributed to temperature effects. Therefore, the results of the peak frequency estimates have been plotted versus temperature.

In Fig. 4(B) 50 averages are used. The same two vibrational peaks are identified in most of the averaged spectrums. However, several misidentified peaks are also being identified due to the decreased signal to noise. Perhaps this could be improved with enhanced signal processing.

These same plots are done as colorized waterfall plots in Fig. 5 that help make the 10 to 12 Hz peak more easily observable. The change in the 10 to 12 Hz peak with the seasonal temperature changes is now clearly observable.

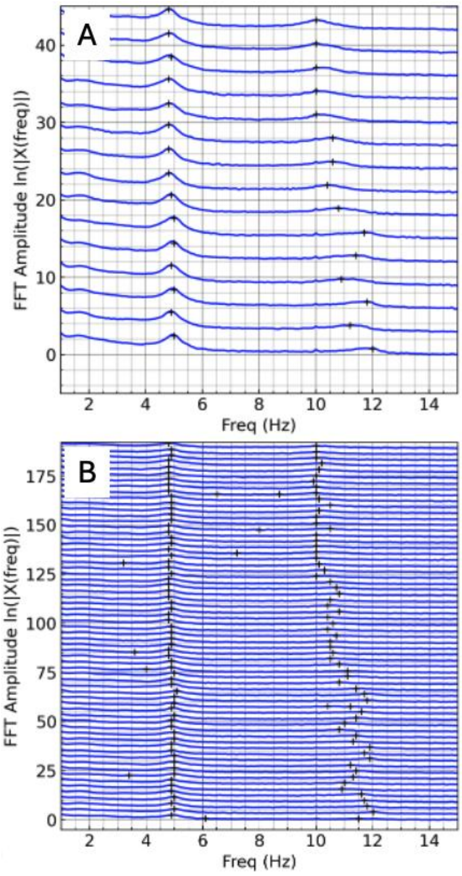

Figure 4. Waterfall vibration spectrum plots for averages of 200 trucks (A) and 50 trucks (B).

The correlation with temperature can be plotted more directly as each spectrum has also has an associated temperature. If we plot the average temperature of each average spectrum against the identified vibrational frequency the correlation is easily identified. In Fig. 6 this has been done for averages of 40, 50 and 200 averages. The peak frequencies are highly correlated with temperature. Although there may be other environmental effects coming into play over this season, temperature would appear to be the dominate influence. Principle component analysis could be used to quantify the effects of temperature versus the time of year. Also, as the number of averages drops below 40 the proportion of misidentified peaks increases rapidly.

Using motion sensors mounted on test vehicles to extract structural vibrational properties as the vehicle passes over the structure is an interesting approach for monitoring fleets of bridges [9]. For this field to advance large data sets of simulated and field observations are needed. Simulated data sets have been created [14]. It might also be possible to create field observation from the benchmark data set. The strain is directly related to displacement and therefore acceleration can also be calculated. Comparing cold and warm weather results would be a good test of damage detection using vehicle derived responses. Another potentially useful case would be if one wanted to simulate the use of a sensor trailer to measure the free vibration [15].

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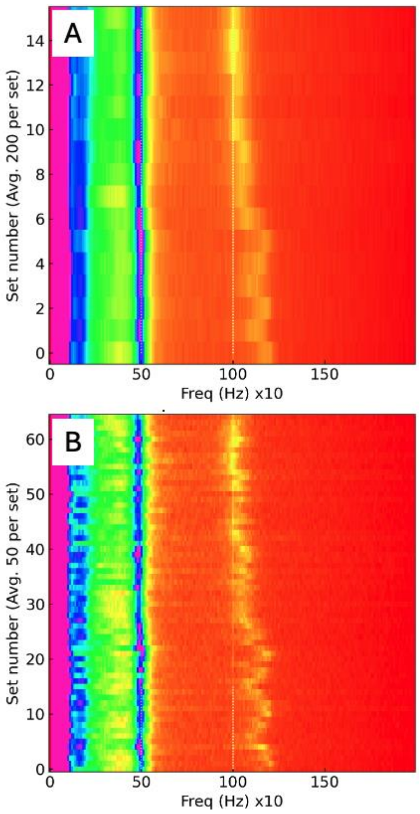

Figure 5. Waterfall vibration spectrum plots for averages of 200 trucks (A) and 50 trucks (B).

Whether or not a damage detection algorithm can detect damage using actual field derived data is often an open question. Only rarely do owners allow full scale structures to be damaged so that actual field responses before and after damage can be obtained [3]. However, temperature changes often lead to significant structural changes due to effects such as due to bearing restraint [5]. A first step towards testing damage detection algorithms could be the detection of temperature induced structural changes. Due to the temperature change over the observation period in the benchmark data set there are also significant easily observable structural changes. Evidence for this is the frequency change seen in Fig. 6B, for example. In order, for the frequency to change there must be some significant structural change. The temperature induced structural changes can also be easily observed in the girder distribution factors. Therefore, the data set could be divided into “good” and “damaged” data sets using temperature as a means of sorting. Here the “damaged” set would not correspond to actual structural damage but would have significant structural differences from the “good” data set. For example, trucks 2300 to 3300 could be chosen as the “good” data set and used to train an algorithm. Trucks could then be chosen to test a detection method. Trucks with larger temperature differences compared to the “good” set would have larger structural differences. This provides a means to quantitively test detection algorithms. One could argue that these only tests detection of a particular type of structural change. However, this change does include changes in girder distribution factors, which are one of the common reasons bridge load ratings are reduced [16].

The benchmark data set also includes strains from multiple sections and it might also be possible to also extract vibrational mode shape information.

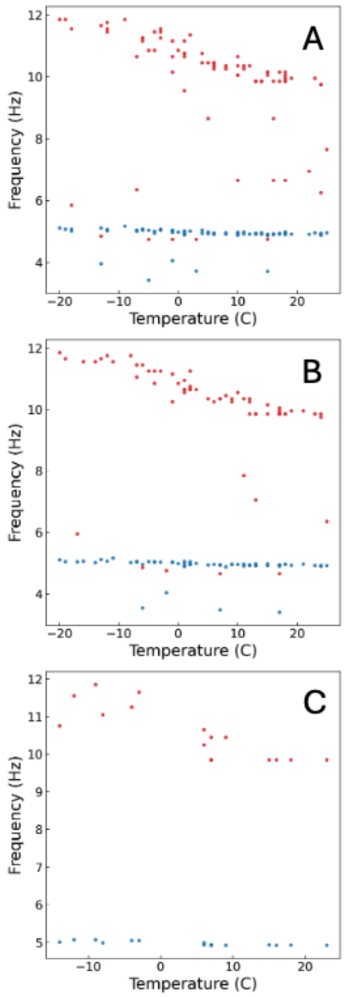

Figure 6. Plots of frequency peaks for averages of 40 trucks (A), 50 trucks (B)and 200 trucks (C).

4 CONCLUSIONS

The sampled strain data from the benchmark data set can be used to extract vibrational frequency spectrums. The passages from several trucks need to be averaged to extract consistent vibrational peaks. Typically, 40 to 50 trucks are required. Temperature induced changes in the vibrational peaks can easily be observed. The temperature induced structural changes might be the basis training and testing data sets that could be used to evaluate the effectiveness of some damage detection algorithms.

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