Bridge-Vehicle Interaction Analysis Based on Continuous GPS/IMU Vehicle Recordings and GBMI Bridge Measurements: Preliminary Results and Investigations

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Abstract. This paper presents preliminary results from the experimental investigation of a bridge-vehicle dynamic analysis study based on vibration recordings obtained at a single span, cable-stayed bridge and a moving vehicle for a number of running and braking tests at various speeds. Deck vibrations are measured using a Ground-Based Microwave Interferometer (GBMI) unit, whereas vehicle kinematics are captured using a high-end GPS/IMU system. Data processing relies on the computation of the bridge and vehicle vibration spectra and their corresponding Short Time Frequency Transform (STFT) diagrams. Analysis unveils the dynamic influence between the two systems, particularly considering the modal frequencies of the deck, derived through Operational Modal Analysis (OMA).

Keywords. bridge-vehicle interaction, radar intereferometry, dynamic displacements, STFT, DAF

1 Introduction

Nowadays, non-destructive testing (NDT) techniques are widely used in bridge engineering to evaluate the structural integrity of bridges as a tool for damage detection and for proactive rehabilitation at the various stages of their operation. Three general types of NDT techniques exist. Static load tests are used to assess the actual response of a bridge and to assist in numerical model updating under static load conditions (Brownjohn *et al* ((2010), Gikas (2012), Gikas *et al* (2014a)). Ambient vibration tests aim at studying the actual behavior of a bridge under operational loads including normal traffic and environmental effects. In this case Operational Modal Analysis (OMA) techniques are used to compute the natural frequencies, the modal shapes and damping factors of the structure (Brincker *et al* (2000), Brincker *et al* (2010)). Finally, dynamic load tests are employed to evaluate the actual response of a bridge under dynamic load conditions, usually realized via a heavy vehicle passing over the bridge at various speeds (Lin *et al* (2005)).

In this study, the interest is placed on bridge dynamic load testing NDT. More specifically, it concerns with a generic problem in bridge engineering, known as “bridge-vehicle interaction” that studies the influence that a moving load (i.e. vehicle) imposes on the bridge and vice versa (Yang *et al* (2005), Zong *et al* (2015)). Specifically, the paper presents the testing procedures and preliminary results obtained from an experimental bridge-vehicle interaction investigation, undertaken at a single-span, stayed-cable bridge. In order to study the interrelated dynamic effects that evolve between the moving vehicle and the structure, a number of testing scenarios are employed, while the kinematics of the vehicle and the bridge deck are recorded continuously using a tactical-grade GPS/IMU system and a Ground-Based Microwave Interferometer (GBMI) radar (Pieracinni (2013), Kuras and Ortyl (2014)), respectively. Data analysis includes time and frequency analysis of the deck response and vehicle kinematics, Dynamic Amplification Factor (DAF) computation of the bridge deck, as well as, bridge-vehicle interaction analyses obtained through studying the Sort Time Fourier Transform (STFT) plots of the data obtained from the test vehicle and bridge deck.

2 The Bridge-Vehicle Interaction Problem

As a vehicle passes over a bridge it generates deflections and stresses that are generally greater and more complex compared with those caused by the same vehicular loads applied statically. Due to the dynamic character of the problem, bridge-vehicle interaction is a rather complicated matter, the solution of which is primarily governed by three factors; namely, the bridge dynamic characteristics (i.e. geometry, dimensions, mass, stiffness, etc.), the vehicle dynamic characteristics (i.e. number of axles, axle load and spacing, suspension, mass, speed, etc.) and their interrelation realized through their respective masses ratio and their matching frequencies *(Yang et al* (2005), Zong *et al* (2015)). Therefore, at a design stage and during the lifetime of a bridge, experimental investigation would help to reveal its actual dynamic properties and assist in the diagnosis of fault indications at an early stage.

While great advances have been made in the analytical modeling of the bridge-vehicle interaction problem since long time ago (Yang *et al* (2005)), in recent years, experimental testing has attracted the attention of many researchers thanks to the improvements in wireless sensor technologies and big data handling computational tools (Kim *et al* (2012), Yi *et al* (2014)). However, despite the great progress in the field, the solution to the problem is still not mature and further research is required in order to integrate the efforts undertaken through the analytical and experimental approaches.

3 Test Bridge Details, Dynamic Testing Scenarios and Instrumentation

The bridge under investigation is a single-span, cable-stayed composite roadway bridge 55.5 m long and variable width ranging between 13.4 m and 18.5 m. It features two Λ-shaped pylons, 18.5 m tall, situated on the one side of the deck. The deck is suspended by six cables (three from each deck side) from two pylons, as shown in Figure 1.

Dynamic loading was undertaken using a three-axle truck with a gross mass of 30 tons and maximum wheel base of 4.65 m. The monitoring system consists of a ground-based microwave interferometer (IBIS-S, IDS SpA) used to record the dynamic settlements at the one side of the deck. More specifically, the vibrations occurred at the deck locations realized by the three cable anchor points were recorded at a sampling frequency of 60 Hz.

Also, in order to obtain the complete track history of the test vehicle kinematics, a geodetic-grade accuracy GPS/IMU system (SPAN, NovAtel) was operated on the vehicle during tests, at a sampling frequency of 200 Hz.

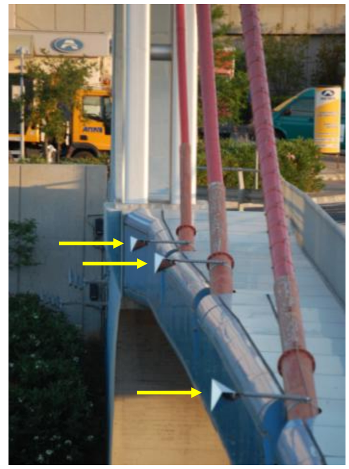

Fig 1. Bridge under test.

The IMU (Inertial Measurement Unit) was fixed on the truck chassis, whereas the GPS antenna was placed over the top of the truck to ensure good satellite availability (Figure 2). The excitation of the bridge was realized through a number of dynamic scenarios that include crossing the bridge at constant speeds, abrupt braking, passing through obstacles and stimulating a mechanical beat via free-falling of the rear part of the truck using a wooden beam.

Fig. 2 Test vehicle with the GPS/IMU unit and GPS antenna fixed on it.

4. Data Processing and Analysis Steps

Processing of the raw data has undergone through a complete series of computational steps that are not fully realized in this study. In summary, GBMI dynamic displacements were processed at the frequency domain to produce the Power Spectral Density (PSD) estimates of the bridge deck at the three target locations. This was followed by an STFT (Short Time Fourier Transform) analysis employed to reveal the evolution in the deck frequency content as the signal varies with time (Hoa *et al* (2010)).

The vehicle GPS/IMU measurements were initially processed through a Kalman filtering algorithm to compute the filtered track trajectory and kinematics for the complete test sequence. Then, in a similar manner to bridge data analysis, the vertical acceleration component was processed at the frequency domain to produce the truck PSD and STFT analyses.

Therefore, based on the STFT plots for the bridge deck and those derived for the test vehicle, a preliminary bridge-vehicle interaction analysis was performed that revealed the mechanism with which the dominant frequencies of the bridge deck spectra run through the moving vehicle and vice versa. The arguments of our analysis were reinforced further using knowledge of the deck modal frequencies, identified in previous analysis undertaken by the authors (Gikas *et al* (2014b), Gikas *et al* (2014c)). More specifically, full attention was paid on investigations concerning the first modal frequency of the deck, as it is the most critical one and characterizes the performance of the structure. Finally, data analysis involved the DAF computation of the bridge deck. DAF is the ratio of the maximum deck dynamic settlement to the maximum static settlement induced using a load of the same size at the same position. In effect, DAF characterizes the excessive response of a deck imposed by a dynamic load compared to its corresponding static load, and therefore, is considered critical in bridge-vehicle interaction analysis.

5. Preliminary Results and Discussion

This paper discusses the preliminary results obtained for two types of dynamic tests; namely, vehicle running and vehicle abrupt braking tests. Figure 3 shows the timeseries of the dynamic displacements obtained at the three GBMI targets placed by the short, middle and long cables on the deck, during the time it has taken the vehicle to run through the bridge at a constant speed of 20km/h (Fig. 3, left) and during an abrupt brake event that took place at about 2/3 of the bridge deck length (Fig. 3, right). A number of points is directly evident from these plots. The first thing to note regarding the vehicle run test is the substantially larger displacements observed at the GBMI target placed by the long cable, compared to those recorded at the target locations placed by the short and middle ones. As expected, this observation confirms the decreasing influence of the pylon on the deck response as the truck moves away from it. Moreover, the high resolution in the GBMI measurements reveals clearly the time lag observed between the maximum displacement values for adjacent GBMI targets. This phenomenon shows up clearly in the inset plot of Figure 3, and verifies the fact that maximum settlement value is anticipated for the time instant the moving vehicle is passing by the target locations.

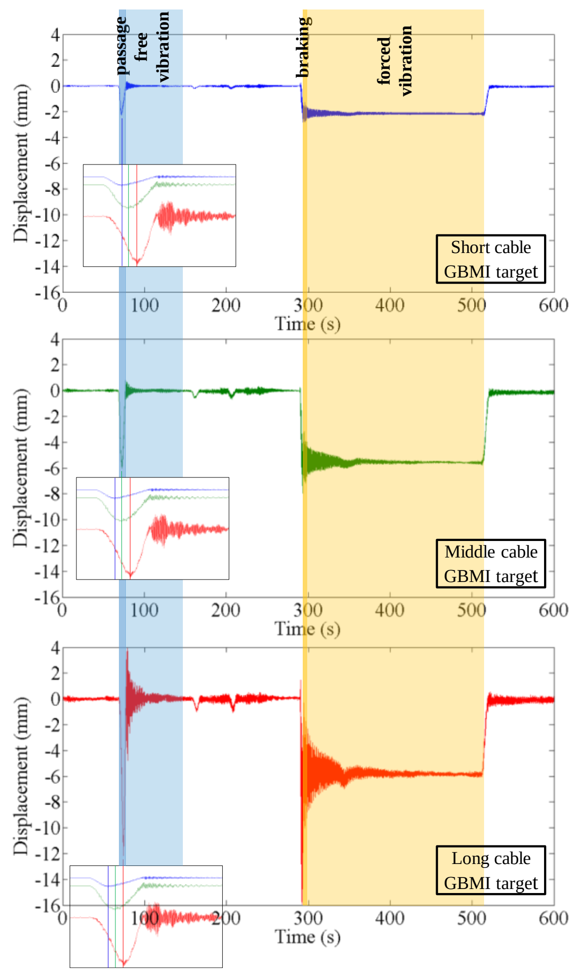

Fig. 3 Dynamic displacements observed using the GBMI unit at the bridge deck realized at three locations, by the short (top), middle (middle) and long (bottom) cable anchor points.

Furthermore, the sequence in the appearance of the maximum displacements indicates the truck passing direction as it moves from the short towards the long cable. Cross-comparisons of the dynamic displacement patterns observed between the running and braking events shows a shorter duration effect in the latter case. In fact, this is due to the shorter lasting time of the braking event compared to the time required to complete the running test. On the contrary, the vibration of the bridge deck that follows the braking event has a substantially greater duration compared to the one that follows the truck passing test.

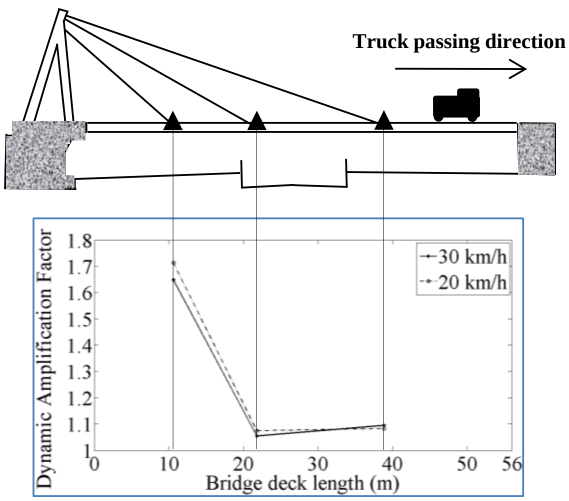

Fig. 4 DAF values computed at the three GBMI targets for two passes of the test vehicle, at travel speeds of 20 km/h and 30 km/h. (GBMI targets shown in triangles).

Figure 4 shows the DAF values computed at the GBMI target locations for the truck passing over the bridge at a constant speed of 20 km/h and 30 km/h. From this plot is apparent that the DAF curves exhibit a similar pattern suggesting consistency in the computations. Examination of Figure 4 in more detail reveals a much higher DAF value for the deck location close by the short cable, compared to the DAF values obtained for the deck locations by middle and long cable anchor points. As expected, this phenomenon reveals the high resistance of the bridge deck to static loadings applied in the short cable area. In contrast, in the area beyond the middle of the deck, the size of the maximum static and dynamic displacements become of a similar size (i.e. the DAF value gets close to unity), as the counteracting influence of the pylon to static loads decreases.

Finally, Figure 5 shows the STFT plots produced for the vibrations of the moving vehicle (top) and the bridge deck location that is realized by the long cable anchor point (bottom), for the vehicle run and sudden braking events shown in Figure 3.

It is known that by the time a heavy vehicle leaves a bridge, the structure experiences a free vibration, and hence, the dominant frequencies observed should correspond to the natural frequencies of the structure. As a result, examination of the STFT plot obtained for the bridge deck indicates that by the time the truck pops out the bridge (~80s), the deck exhibits an excitation response at 1.22 Hz. Interestingly, this peak value coincides with the first modal frequency of the deck identified in previous work undertaken by the authors (Piniotis et al, (2016)). Then, the response frequency at 1.22 Hz remains constant for the time period for which the excitation level is high, and thereinafter it fluctuates around this value until the excitation phenomenon fades out. Moreover, examination of the STFT analysis for the test vehicle reveals the frequency value associated with the truck engine idling at 9.35 Hz. In fact, this finding becomes evident through studying the vehicle frequency content derived for the time interval after the truck has left the bridge and stopped (~140s), waiting stationary until the braking test started (~270s). Then, immediately after the truck brakes (~290s) the bridge deck exhibits a forced vibration as the truck remains stationary on the deck. As expected, the peak frequency at 1.22 Hz decreases to 1.19 Hz, due to the stationary truck mass applied on the deck. Notably, as a result of the much stronger excitation induced during the brake event, this frequency value (1.19 Hz) lasts for a longer time period (i.e., from ~295 s to ~ 470s) compared with the one associated with the truck passage test (i.e., from ~80s to ~140s). Interestingly, the frequency value at 1.19 Hz can also be clearly seen in the STFT plot of the truck data for the time span (i.e. from ~305s to ~470s) the truck remains stationary on the bridge deck. Obviously, for the same time period the truck engine idling frequency observed at 9.35 Hz is evident in the STFT plot of the truck data, since the truck engine remained in idle operation.

Notably, in the foregoing discussion, and in order to clearly show up the driving frequency underlying the maneuvering events in question, a programming software was developed to detect and depict (blue and red line in Fig. 3) the frequency value in the STFT data with maximum magnitude. Particularly, this task was undertaken in the data range of the first modal frequency of the deck (1.22 Hz) and in the frequency band of the truck engine idling (9.35 Hz).

6. Concluding Remarks

This paper presented preliminary results from the experimental investigation of a bridge-vehicle interaction study, based on contemporary sensor data recordings. The high quality, high sampling rate vibration measurements and the good data synchronization allowed to detect and identify the frequency effects imposed from the running vehicle on the deck bridge and vice versa. More specifically, analysis has identified the dominant frequencies of the deck and realized the effects that the stationary load (i.e. vehicle) imposes on the deck first modal frequency. Also, the dominant frequency was identified in the truck spectra and STFT plots during the tests.

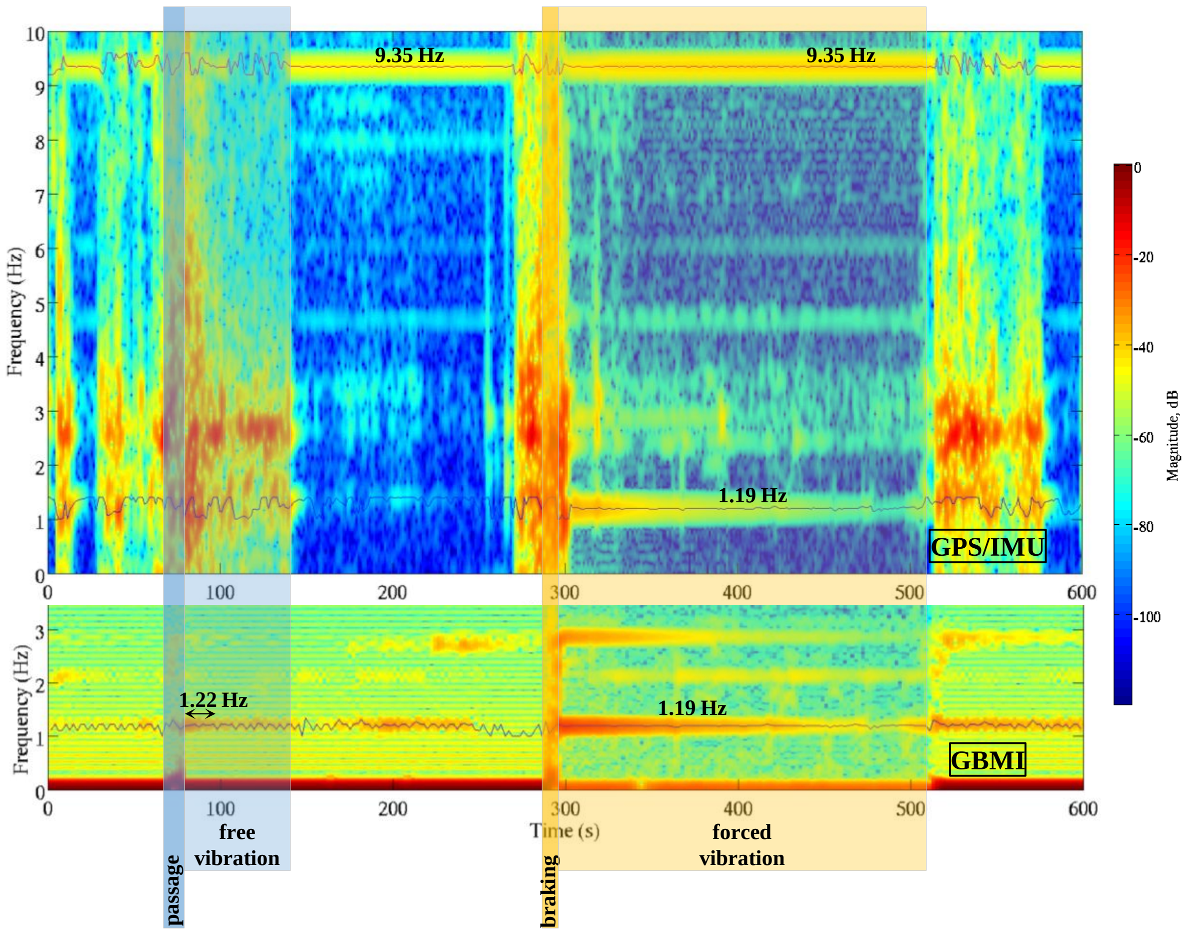

Fig. 5 STFT plots obtained for the vertical acceleration of the vehicle (top) and dynamic settlement at the GBMI target at the deck by the long cable anchor point (bottom). The left part of the plot refers to a single passage of the vehicle at 20 km/h, whereas the right part shows an abrupt braking event.

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