Using Robotic Theodolites (RTS) in Structural Health Monitoring of Short-span Railway Bridges

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ABSTRACT:

Measurement of deflections of railway bridges when they are crossed by trains is important for the design and evaluation of their structural health. In this paper are presented the results of RTS monitoring of the Gorgopotamos Railway bridge in central Greece, a bridge >100 years old with several openings of ~30m. This bridge was partly destroyed and rebuilt twice, and its dynamic behavior is practically unknown.Our study focused on the apparent vertical displacements of a reflector set at the midspan of an opening, where maximum displacement was expected, during the passage of trains. A high-rate robotic theodolite (RTS) with upgraded software to record measurements with centi-sec resolution was used. Based on measurements before and after the train passage, i.e. on intervals during which no deflections were expected, the noise level of the vertical deflection was estimated ~1mm. On the contrary, deflections of 6-7mm were observed when trains were passing from the bridge span. The deflection signal was analysed into a semi-static deflection of ~3mm corresponding to the bending of the span during the train passage and an oscillation of ~4-5mm, corresponding to dynamic deflections caused separately by each passing wagon. Obtained results are statistically significant, permit even estimation of reliable spectra of the displacements and consistent with theoretical models. Hence they show the potential of RTS in structural health monitoring.

1. INTRODUCTION

Robotic theodolites have been used for monitoring of semistatic deflections of bridges (Erdogan and Guelal 2009; Koo et al., 2011) relative to a fixed reference frame, but rarely only to record their dynamic displacements (Coser et al., 2003; Lekidis et al., 2005 Psimoulis and Stiros, 2007), despite their advantages not to require unobstructed view of the horizon and not to be affected by multipath, as is the case with GPS (Brunner, 2006).

As is analyzed below, this stems from the fact that most RTS have a low sampling rate (up to 1Hz) and are affected by dynamic errors (mostly jitter and clipping effects) which have hindered their use so far in structural monitoring of rather stiff structures. They have, however, been used in other dynamic measurements (sea-wave characteristics, Psimoulis and Stiros, 2010).

In this paper we summarize data from the RTS monitoring of a short-span historic railroad bridge in Greece and show that RTS, under certain conditions, is suitable for monitoring high-rate, small-amplitude oscillations. In addition, we present a technique to estimate the noise level and assess the accuracy of obtained results.

2. THE GORGOPOTAMOS RAILWAY BRIDGE

The Gorgopotamos Railway Bridge (Fig. 1) is located about 150km northwest of Athens, in central Greece, and was constructed in 1905. The bridge was destroyed and rebuilt twice during Second World War and is still in use.

The bridge has total length of 211m and 32m maximum height. It is curved in plan, consisting of seven sub-linear spans of approximate length of ~30m, which are supported by six pylons. The present-day bridge is a composite structure with a truss deck, two steel pylons and four masonry pylons, as a result of the two reconstructions (Fig. 1).

The dynamic characteristics of the bridge differ from the initial design, and they are unknown. There is however evidence of significant oscillations of the bridge during the passage of trains, which are forced to reduced speed.

Figure 1. The Gorgopotamos Railway Bridge and in the foreground the RTS used for the measurements focusing on reflector at a midspan. An inset shows the prismatic reflector and on top of it the antenna of a GPS, used as a chronograph.

3. INSTRUMENTATION

In our study we used a Leica TCA 1201 RTS (nominal sampling rate 10Hz), with upgraded built-in software to record

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data with 0.01 sec resolution. This permitted precise measurements despite the instability of the sampling rate, 6-7Hz maximum (jitter effect; Psimoulis and Stiros, 2007; Stiros et al., 2008), which is an advantage in spectral analysis (Pytharouli and Stiros, 2008). The RTS was set on stable ground, about 150m away from the bridge, in an area with excellent atmospheric conditions. One AGA prism was fixed on the handrail of the bridge at one of its midspans (i.e. in a point in which max vertical deflections were expected; Fig. 1) and another on top of a pylon, (i.e. in a point in which minimal vertical deflections were expected). On top of the prisms GPS receivers were set (Fig. 1) in order to provide independent timing of the train passage.

4. METHODOLOGY AND FIELD MEASUREMENTS

The aim of our study was to estimate the deflection of the bridge caused by the passing trains. For this reason was focused on the centre of a span where the largest displacements were expected.
Furthermore it was essential to estimate the measurement noise (uncertainty). This was possible on the basis of measurements

1) at the reflector on top of the pylon, where minimal vertical deflections were expected),
2) when no train was passing, and just before and after a train was passing.

Measurements were made in two surveys in different periods of the year, mostly in the morning to avoid scintillation. A number of trains and intervals of no bridge excitation were recorded. In this paper we focus on the discussion of the analysis of results from recordings of one 7-wagon freight train, and of an interval of bridge equilibrium.

5. DATA ANALYSIS

Collected data were transformed into Cartesian coordinates with an axis tangent to the rail at the reflector point (longitudinal axis) and an axis normal to the rail (lateral axis), while the origin corresponded to the mean value of coordinates during intervals in which the bridge was still. Hence, three time series, reflecting the apparent deflections along the longitudinal, lateral and vertical axis were obtained.
Then, using GPS data and optical recordings, it was identified the time the train entered and left the bridge (solid lines, Fig.3) and the time interval during which the train was passing in front of the targets (dotted lines, Fig.3).

5.1 Noise level definition

Data corresponding to the reflector on top of the pylon, and in period no train was passing, conspicuously corresponding to no deflections, were used to define the noise level for each of the three axes. Data are summarized in Figure 3 and show that the noise is of the order of ±1mm, except for the lateral axis, in which the noise for the specific example was ±2mm. This is likely not to reflect a measurement problem but wind-induced oscillation of the handrail along the lateral axis.
The inferred measurement noise level of ±1mm is better than that deduced from experiments (Psimoulis and Stiros, 2007), because the latter corresponded to nearly average conditions, while the Gorgopotamos data to nearly ideal conditions.

5.2 Response to trains

Figure 3 summarizes the apparent displacements of the midspan of the bridge (Fig. 1) when a train of 7 wagons crossed the bridge. Along the lateral and the longitudinal axes the noise level (apparent displacements when the bridge span was not excited) is of the order of ±1mm, while when the train was passing it was up to 6mm, clearly above the noise level, indicating a real motion.

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6. ANALYSIS OF DEFLECTIONS

The vertical deflections of bridge during its excitation by the passing train were decomposed into a high-period and a low-period component, corresponding to semi-static and dynamic displacements (Psimoulis and Stiros, 2007; Moschas and Stiros, 2011). A simple high-pass filter (a moving average filter with step 21 and overlap 20), deduced from supervised learning-based studies was used. Results are shown in Figure 4.
The long-period component has a trapezoid pattern representing a mean semi-static displacement of ~3mm (horizontal dotted line).

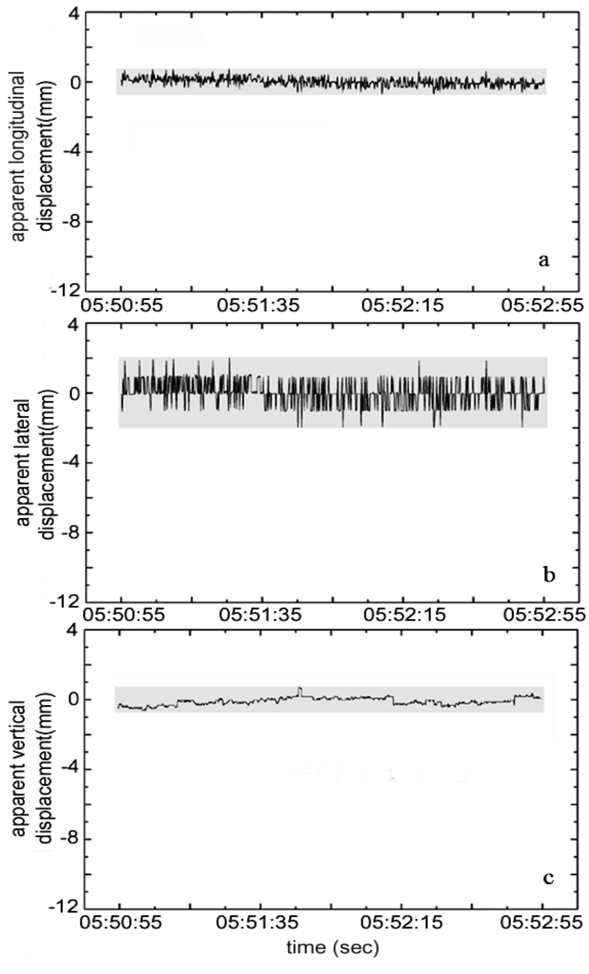

Figure 2: Time series of apparent displacements along the longitudinal, lateral and vertical axes corresponding to the point over the pylon, while no train was passing. The noise level (shaded zone) in the vertical axis was ±1mm, but along the lateral axis ±2mm, probably because of wind-induced lateral oscillations of the handrail of the bridge.

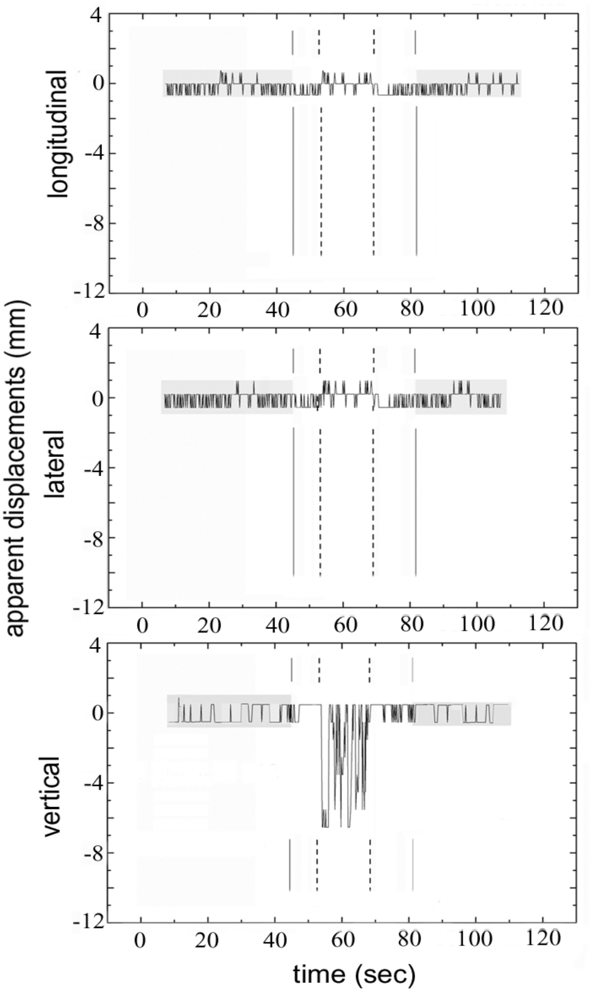

Figure 3. Apparent displacements along the longitudinal, lateral and vertical axes describing the excitation of the bridge by a 7-wagon passing freight train. The vertical solid vertical lines define the interval of the passage of the train from the bridge and the dotted ones the interval during which the train was passing in front of the current reflector. Grey zones indicate measurement noise, of maximum amplitude ±1mm. Only the time series of the vertical axis reveals real displacement, ~6mm exceeding the amplitude of the noise (~1mm).

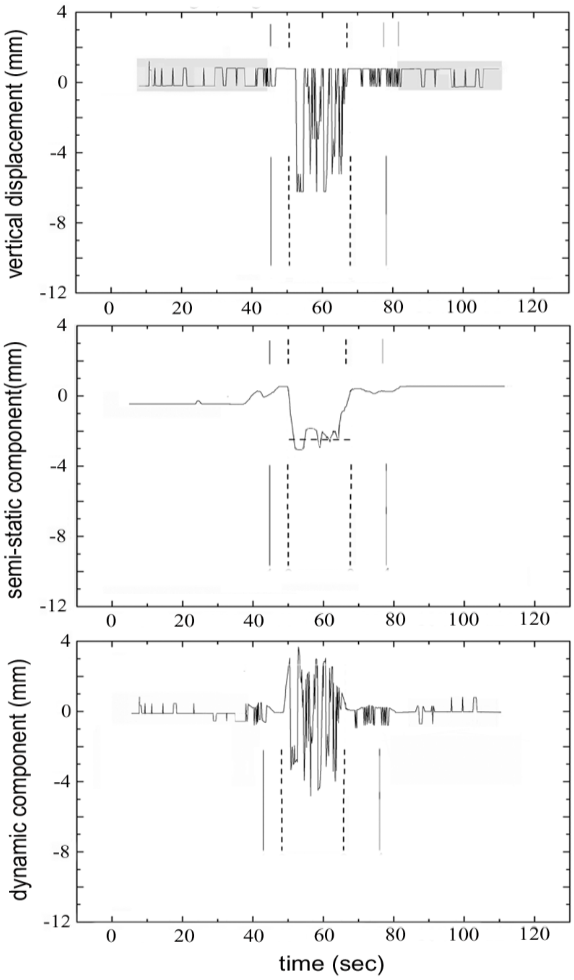

Figure 4. Decomposition of the apparent vertical displacements (top) into long (middle) and short-period components (bottom), corresponding to semi-static and dynamic displacements. Shading indicates noise.

The short-period component has a wave-form pattern, corresponding to an oscillation with mean amplitude ±4mm and very much consistent with that derived for other train bridges on the basis of FEM analysis (Xia and Zhang, 2005).

The short-period component, however, is characterized by clipping, i.e. loss of some oscillation cycles; an effect characteristic of dynamic measurements at the limit of the instrument operation. This is one of the reasons why this waveform does not correspond to the number of wagons (see Psimoulis and Stiros 2011).

7. CONCLUSIONS

The output of this study is that RTS permitted to record the deflections of the midspan of a 30m long opening of the historical Gorgopotamos bridge when excited by a passing train. It was found that only the vertical deflections were significant, up to ~±6mm), clearly above the measurement noise (±1mm). The latter was defined (1) by comparison of recorded apparent displacements before, during and after the train passage (i.e. before, during and after the excitation intervals); (2) by comparison of recordings of apparent displacements of points in which no deflections were expected (on top of pylons) and those for which deflections were expected; and (3) experimental data (Psimoulis and Stiros, 2007). These indicate that the proposed method cannot only permit the measurement of small-amplitude deflections, but also an assessment of their accuracy.

Obtained results are consistent with FEM-modeled deflections of bridges and indicate that RTS is a powerful tool in structural health monitoring.

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