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Response of a historical short-span railway bridge to passing trains: 3-D deflections and dominant frequencies derived from Robotic Total Station (RTS) measurements

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ABSTRACT

Based on measurements with a Robotic Total Station (RTS), we computed the displacement characteristics (pattern, amplitude, frequency) of the Gorgopotamos Bridge, a short-span, historical bridge in central Greece, in response to passing trains. Vertical deflections of selected points of the midspan were found to range up to 6 mm for heavy cargo trains, exceeding the noise level of 1–2 mm, and were analyzed in nearly semi-static and dynamic components. Dominant frequencies of the bridge span, in the range 3.18–3.63 Hz, were also computed. Evidence of possible lateral and longitudinal deflections was also found. Measurement noise and quality of results were controlled on the basis of the analysis of apparent displacements of reference points during excitation and of non-excitation intervals, as well as on the basis of structural constraints. The amplitude of measured deflections was found to correlate with the load, and a somewhat distinct oscillation waveform was observed in the cases of large oscillations, despite clipping affecting highly dynamic RTS recordings. Observed deflections are large for modern standards, but reasonable for a >100 years old bridge partly destroyed and rebuilt twice during World War II.

1. Introduction

In the last years there has been a broad interest for the measurement of deflections of various engineering structures in response to dynamic loads (traffic load, wind, earthquakes [1–6]), and to quasi-static loads (mostly temperature effects [7–9]). The basic reasons were to monitor their structural health (especially changes in their structural characteristics due to aging, earthquake, etc. damage or post-damage repairs [10–12]) and to use load-imposed deflections as input in their design [13,14].

A major limitation in the measurement of deflections has been the availability of the appropriate instrumentation, i.e. of instruments that can measure absolute displacements, i.e. displacements in a reference frame independent of the structure. This is a problem that has been first faced in the Eiffel Tower in the 19th century, when deflections of the top of the Tower had been recorded using conventional theodolites [15]; at this time, however, measurements of only semi-static deflections of the Tower were possible.

In this article we discuss the results of a detailed study of application of RTS (Robotic Theodolite or Robotic Total Station, or TPS) in the measurement of the deflections of a historical bridge, the Gorgopotamos Bridge in central Greece in response to passing trains. RTS, practically introduced in the last decade, is a high quality total station equipped with an automatic target recognition device (ATR) and a servo-mechanism which permit to identify and lock into a certain target, preferably a prismatic reflector, and to track and record its movement [16].

RTS has been used in a few cases for the monitoring mostly of suspension bridges [17,18], and especially for the study of their long-term deformations, mostly temperature-induced [8,9], while its potential for the monitoring especially of stiff bridges was rather underestimated, mainly because of the limitations of this instrument, discussed below.

In the present article, on the base of the analysis of the Gorgopotamos Bridge, we assess the potential of RTS to accurately record 3-D deflections of structures with an accuracy of a few millimeters for oscillations up to 4 Hz. This study indeed follows preliminary report of the response of this bridge to passing trains and analysis of experimental results [16,19–21].

The key points of the present study are:

(1) We analyze the sensitivity of the study bridge to different dynamic loads (i.e. different types of trains); this result is important to put some limits to the speed of trains crossing this, and eventually other somewhat similar bridges.

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(2) We analyze the response of the bridge to dynamic loads in different environmental conditions, both concerning the medium through which the RTS ray was passing (i.e. atmospheric turbulence, etc.) and the response of the bridge foundations in different environmental conditions (saturated and non-saturated argillaceous rocks).
(3) We introduce or describe structural, logical and computational constraints to the estimation of the level of noise in geodetic and other measurements of this and of other structures excited by dynamic loads. This quasi-deterministic approach overcomes the difficulties of stochastic estimates of noise, mostly based on *a priori* assumptions of measurement errors and/or on the application of the law of error propagation [22,23].

The results presented above determine the limits of the application of RTS currently available in structural engineering, as well as in other applications of guidance and control in positioning (robotics for instance).

2. Structural monitoring with RTS – principles, requirements and limitations

RTS is a new generation total station instrument, equipped with an automatic target recognition device (ATR) which permits to identify and lock into a certain target, preferably a prismatic reflector, and a servo-mechanism which permits to track the target. The image of the reflector is recorded by a CCD camera embedded in the RTS telescope, and the servo-mechanism is activated in order to minimize the distance of the image of the reflector from the center of the CCD monitor, i.e. from the telescope axis. Measurements of the zenith and horizontal angles are made, and in addition, a modulated IR or laser ray is emitted from the RTS to the reflector (target), is received back and is analyzed by the instrument microprocessor. The instantaneous measurement of the distance between instrument and target, up to a few hundred meters, is combined with the measurement of a vertical and a horizontal angle and hence instantaneous 3-D polar coordinates of the moving target are recorded with mm resolution and with real frequency exceeding 5 Hz (nominally 10 Hz) for certain instruments. Obtained polar coordinates can then be transformed into a selected Cartesian coordinate system.

The details of RTS operation and reports for its application in dynamic measurements are discussed in [16,24–27]. However, in most of the cases low-quality or multi-prisms were used, and this leads to overall low-quality results. This is because the focal (reference or central) point of the reflector may not be stable, and in practice the RTS receives and mixes information from different reference points [28]. However, supervised-learning experiments revealed that selected RTS, in combination with high-quality AGA type reflectors with a very stable focal (reference) point, permit to record small-amplitude, high-frequency (even above 3 Hz) scale dynamic displacements with accuracy of a few mm even at average atmospheric conditions [19,29]. A requirement for that is that atmospheric turbulence, representing the major threat for optical measurements, is avoided, and that the reflectors permit stable and unique focus, as well as identical paths for the ongoing and returning ray. All these are possible for old reflectors used in the past for long-range electronic distance measurements (EDM), especially the AGA-type reflectors. Such reflectors consist of several reflecting surfaces with a very precise geometry, so that the oncoming ray is reflected successively on several surfaces, is guided to the (unique) center of the reflector, and then follows exactly the same path back to the RTS with a minimum loss of its energy.

Systematic, supervised-learning experiments [19,29] and field surveys [16,20] revealed three main problems for high-rate RTS measurements: the jitter, the clipping and the synchronization effects.

First, RTS at its maximum sampling rate is characterized by an unstable sampling rate [16,24,30], as is the case with all electronic instruments ("jitter effect"). The latter can be overcome using upgraded built-in software which records time with resolution of 0.01 s. The output time series correspond to an unstable sampling rate, and this is indeed an advantage, because if time series are analyzed with a suitable software, not subjected to the limitation of FFT, the obtained spectra can exceed the level of the Nyquist frequency (see Section 8.2) [31]. Hence, a RTS with a real sampling frequency of 5–7 Hz can safely measure spectral peaks of the order of 4 Hz (see [19,29]).

Second, high-frequency RTS dynamic measurements are contaminated by dynamic noise, mostly clipping, again characterizing nearly all electronic and other recording instruments; in particular, some oscillation peaks are mis-recorded or even whole cycles of oscillation are lost. This is the most serious problem with RTS, but once understood, results can be controlled using for instance certain filtering algorithms [19].

Third, synchronization between various sensors. This is a problem examined elsewhere and arising from the fact that most RTS have an internal clock, recording in an unknown phase with recordings of other sensors. In this particular case we took advantage of the high-multipath produced by the passing train in the GPS recordings [32,33] and used the corresponding signal as chronograph stamp for the timing of the passing of the train in front of certain RTS reflectors.

A final problem is that of outliers, again common in all measurements. Our experiments have shown that the frequency of their occurrence in RTS is small, but still they may exist. Outliers were identified using a typical stochastic approach (3-sigma criterion; [34]) and were removed using logical/structural criteria.

3. The Gorgopotamos Railway Bridge

The Gorgopotamos Railway Bridge (Fig. 1), constructed in 1905, is located close to the town of Lamia (central Greece), about 150 km NW of Athens. During World War II the bridge was partly destroyed and rebuilt twice. More specifically the spans 1, 2 and 3 (spans closer to Athens direction) were destroyed in 1942 while

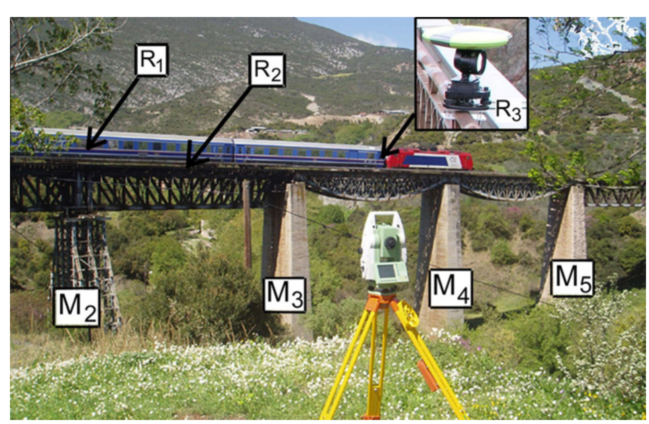

Fig. 1. The Gorgopotamos Railway Bridge and in the foreground the RTS used for the measurements. An inset shows the prismatic reflector R_3 with a GPS antenna on top of it. The location of the two other measuring points R_1 and R_2 are shown. Pylons M_3 to M_5 and the span between them derive from the original 1905 construction. Differences in the length of wagons are responsible for different excitation frequencies.