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Non-contact measurement of the dynamic displacement of railway bridges using an advanced video-based system

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ABSTRACT

This article describes the development of a non-contact dynamic displacement measurement system for railway bridges based on video technology. The system, consisting of a high speed video camera, an optical lens, lighting lamps and a precision target, can perform measurements with acquisition frame rates ranging from 64 fps to 500 fps, and be articulated with other measurement systems, which promotes its integration in structural health monitoring (SHM) systems. Preliminary tests of the system have shown that the measurements' precision can be affected by: (i) movements of the camera stand and, therefore, rigid supports should be used and the camera should be protected from air flows; (ii) the distortion of the field of view, caused by the flow of heat waves generated by IR incandescent lighting and, therefore, the operating time of the lamps should be limited. The system was used to measure the displacement of a railway bridge's deck, induced by the passage of trains at speeds between 120 km/h and 180 km/h, yielding a very good agreement between the results of displacement measurement obtained with the video system and with a LVDT. The achieved precision was below 0.1 mm for distances from the camera to the target up to 15 m, and in the order of 0.25 mm for a distance of 25 m. The application of an image processing technique at subpixel level resulted in real precisions generally inferior to the theoretical precisions.

1. Introduction

The monitoring of the structural integrity of bridges is a current and relevant topic of research in structural engineering, motivated by the need of the owners and managers of infrastructures to reduce the costs of inspection and maintenance, while ensuring that the structural behavior and the security level are appropriate throughout the bridge's useful life [1-5]. This monitoring is based on the continuous or periodical acquisition of an appropriate set of relevant measures of the structural response based on a network of transducers.

For railway bridges, one of the most relevant measures of the structural response is the dynamic displacement of the structure due to the passage of trains [6-8]. The displacement measurement systems can be classified as contact and non-contact measurement systems [3,4,6].

The contact systems generally encompass high precision displacement transducers, such as LVDT and cable type. The main disadvantage of these systems is their dependence on a reference because they are based on the relative displacement measurement between a point of the structure and a close point that can be considered fixed. This fixed point can, in many instances, be difficult, or even impossible, to materialize as, for example, when the structure is located over a watercourse, a road or in a rugged terrain, etc.

The non-contact measurement systems rely on laser technology [9], radar technology [10,11], GPS technology [12,13] and on the processing and analysis of images obtained by video technology [2,3,5,7,14-16] or digital photography [1,17-19]. Some authors combine these technologies [20,21] to enhance the overall performance of the measurement system.

Systems based on laser technology are generally very precise, with accuracies between 0.1 mm and 0.2 mm [22]. However, they are very costly and their application for long distance measurements involves the use of a high intensity laser beam that can endanger human health [9]. The main disadvantages are the high cost and the inability to measure displacements perpendicularly to the laser beam [11].

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Systems based on radar technology ensure a very good resolution, with accuracies better than 0.02 mm [23], and allow the performance of measurements over long distances and from multiple points simultaneously, even under unfavorable weather conditions [10].

Systems that utilize GPS receivers' technology to measure the displacements of structures, particularly large span bridges [12], have been developed recently. These systems still have limited precision, usually between 5 mm and 10 mm [13], but that can be enhanced to about 0.2 mm with the use of local stations [24]. Other disadvantages are the high cost and the limited acquisition frequency, in most cases below 20 Hz [24].

The application of video technology based systems in the measurement of dynamic displacement of bridges due to high speed rail traffic is only briefly reported in the literature. The study carried out by Lee et al. [6] on the measurements of a railway bridge of the Korean high speed railway network was the only one identified.

Systems based on image processing have the advantage of establishing a good compromise between the acquisition frame rate and the resolution [25]. These systems usually include a video camera, an optical lens, lighting lamps and a precision target fixed to the structure. Typical resolutions obtained in displacement measurements of bridges are within 0.1 mm, for distances of 10 m between the video camera and target, and 1.0 mm, for a distance of 100 m [12]. These systems have been used in static and quasi-static measurements for the performance of load tests on bridges [1-3,5,17,26]. Measurements are usually two-dimensional [2] using a single video camera, but can be three-dimensional using two video cameras [14].

For the image processing procedure there are generally two options: the use of techniques based on the tracking of a set of characteristic points extracted from the images [2,3,5,8] or the use of all information present in the images [6].

Concerning the characteristic points, they generally correspond to the transition points between the black and the white regions of a target. The application of this technique depends on the particular characteristics of each precision target. In some situations, the tracking is reduced to a single reference point, such as a vertex of a black or white area [2]. More recently Bell et al. [1] and Malesa et al. [7] applied a technique that does not require a target because it only uses one set of pixels to define a pattern or texture of the structure. This technique, often referred to as Digital Image Correlation (DIC), locates the pattern pixels of each image through a correlation analysis at subpixel level [19,26].

The techniques that use the entire images information normally resort to mathematical operations involving the matrices that contain color information of the pixels that form each image, typically in a gray scale, before and after the movement. The application of such techniques is reported in the studies carried out by Olaszek [8] and Lee et al. [6].

Globally, concerning the image processing approaches, Olaszek [8] pointed out some factors that may affect the precision of the video system, such as the dimensional precision of the target, the lighting, the light refraction phenomena, the phenomena of image distortion caused by the optical elements and the image processing. Choi et al. [27] also demonstrate that resizing the region of interest and updating the image resolution during measurement can significantly improve the precision of the video system. Lee et al. [6] also point out some external factors that seem to influence the system's performance, such as precipitation, fog, variation of natural light, and wind action that can induce movements of the camera stands.

This article describes the development of a non-contact dynamic displacement measurement system based on video technology, and its application to laboratory and field testing.

The measurement system consists of a high speed video camera, an optical lens, lighting lamps and a precision target. The system has the following main advantages: versatility, as it can easily be articulated with other measuring systems, it can be programmed for acquisition frame rates from 64 fps to 500 fps, and it can perform dynamic displacement measurements for distances from the camera to the target up to 25 m with high precision, resorting to duplicators or to a duplicator associated with a quadruplicator and a suitable target illumination.

A routine of automatic tracking of the target's points was developed for the image processing, in which some innovative features were implemented, including the detection of transition points of the images' colors based on the RANSAC algorithm [28], and the stability analysis of the initial coordinates of the target, through a statistical analysis of the samples based on percentiles and on the Boxplot diagram [29].

The system's performance was evaluated based on two tests, one in the laboratory and other on the field. The laboratory test evaluated the performance of the system in measuring the displacement of a steel beam, subjected to a point load applied statically and dynamically, for distances from the camera to the target between 3 m and 15 m. The laboratory test also assessed the influence on measurement precision of factors related to the system itself, such as lighting, the stiffness of the camera stand and the magnification elements. The field test allowed to evaluate the system's performance in the dynamic measurement of the displacement of a point on the deck of a railway bridge, induced by passing trains at speeds between 120 km/h and 180 km/h, for distances from the camera to the target up to 25 m.

2. Measurement system based on video technology

2.1. Architecture

The measurement system based on video technology comprises the components presented in Fig. 1.

The main component of the system encompasses the high speed video camera, the lens and the magnification elements. The GENIE video camera, model H1400, has a maximum resolution of 1400 × 1024 pixels and an adjustable acquisition frame rate up to 500 fps. This camera presents the highest sensitivity in wavelengths between 600 nm and 700 nm, located in the area of the near-infrared. It is equipped with a Nikon lens model 80-400 VR F/4.5-5.6D ED. The magnification elements (duplicator and quadruplicator) enable to increase the depth of the field of view, and are useful in situations involving high distances between the video camera and the object.

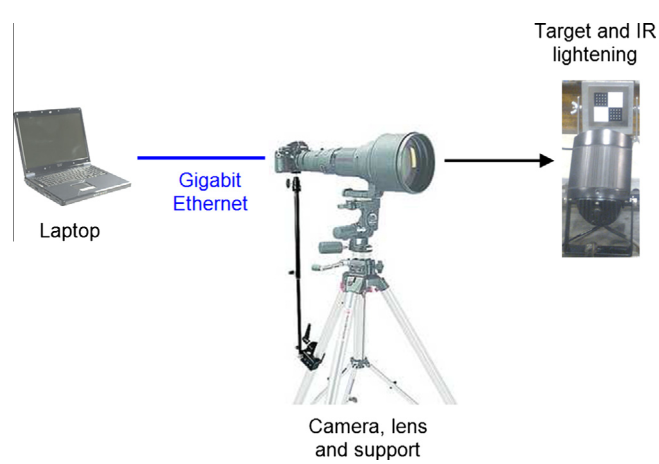

Fig. 1. Measurement system based on video technology.