Surface deflection measurement using structured light

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Abstract

Bearing capacity of road pavement is essential for optimum planning of road maintenance and rehabilitation. Maximum deflection is usually measured by punctual mechanical sensors at low speed (less than 10km/h) which implies safety problems and discontinuous measurements. Moreover, pavement simulations showed that parameters describing the deflection basin are more sensitive to pavement damages than the maximum deflection. This is the case for example for cracking or delamination which could be detected by the radius of curvature or the deflection slope at a fixed distance from the load. A direct measurement of surface deflection could be very useful to estimate such parameters. A new measurement system based on imaging technology has been studied. This non-destructive method consists in the projection of a structured light on the road pavement and allows measuring a surface deflection and its gradient. A first experiment was carried out with a static system on the LCPC test track. The imaging technique was able to measure a surface deflection with satisfactory metrological performance.

Résumé

La capacité de portance des chaussées est une information essentielle pour optimiser la gestion et l’entretien des routes. Elle s’estime par la déflexion maximale. Celle-ci est mesurée ponctuellement par des capteurs mécaniques ce qui pose des problèmes d’interprétation, due à la discontinuité de la mesure et de sécurité liés à la faible vitesse d’auscultation. Des simulations numériques montrent également que la déflexion maximale est moins sensible à des dommages localisés que d’autres paramètres issus du bassin de déflexion. Ainsi, sa pente, à une distance fixe de la charge, ou son rayon de courbure sont plus sensibles à la présence de fissures internes ou de délaminations d’interface que la déflexion maximale. Nous avons étudié une nouvelle méthode de mesure basée sur une technique d’imagerie qui permettrait de mesurer une surface de déflexion, et d’en déduire aisément de tels paramètres. La technique consiste à projeter une lumière structurée à la surface de la route et à observer la déformation de l’image sous l’influence de la charge. Une première expérimentation, conduite sur le manège de fatigue du LCPC avec un système statique, montre que les performances métrologiques du système sont suffisantes pour mesurer un bassin de déflexion.

Keywords

structured light, deflection basin, radius of curvature, continuous measurement
1 Introduction

Deflection measurement is a first element in evaluating roads bearing capacity. Operational devices measure deflection at different distances of a falling or rolling load. This deflection basin is only representative of the neighborhood of the measurement point. It is usually used to estimate the pavement residual life. However, measurements level can quickly change along a roadway. This is well known on concrete pavement by measuring load transfer efficiency at joints [1]. This implies a positioning of the measurement system close to the joint. This is not possible when a continuous wearing course covers the concrete layer.

The objective is to develop a non-destructive, continuous and full view approach in order to evaluate precisely deflection measurement. An imaging technique based on a fringe projection method is studied. It opens the possibility to extend actual deflection measurements and might be the solution to detect road's failure in a non-destructive way. After a description of the imaging technique, a modelisation presents the influence of the possible failures of the road. Finally an experiment gives an example of the application of this full view approach to deflection measurements.

2 The imaging technique

2.1 The fringe projection method

Shape's measurement from structured light is based on triangulation [2]. Contrary to ‘Moiré’ methodology, where the interference of two gratings is studied, the technique of fringe projection uses the projection of only one light pattern (line, grid, fringes or more complex pattern) onto an object. This object is observed with a camera from a different viewpoint, making an angle $\alpha$ with the projection direction. Under these conditions of lighting and observation, the resulting distortion of the projected pattern is directly related to the object shape and its height $\Delta h$ is expressed by:

$$\Delta h = \frac{P_p - P_a}{\tan(\alpha)}$$

where $P_p$ is the period of the fringes projected on a planar surface and $P_a$ is the apparent period of the fringes projected on the object and $\alpha$ is the angle between the incidence of light and the observation directions (Fig. 1).

![Fig 1: Principle of the fringe projection method.](image)

When projecting sinusoidal fringes, the light intensity recorded at each point $(x,y)$ is:

$$I(x, y) = I_0(x, y) \cdot (1 + m(x, y) \cdot \cos \varphi(x, y))$$

(2)
where $I_0(x,y)$ is the mean intensity, $m(x,y)$ the fringe contrast and $\varphi(x,y)$ the optical phase. The height information is contained in the phase, so two images are considered. The first one is taken on a reference plane, providing a reference phase map, $\varphi_{\text{ref}}$. The second one is taken on the object computing the phase $\varphi_{\text{object}}$. The height difference $\Delta z(x,y)$ is linearly related to the phase difference $\Delta \varphi(x,y)$:

$$\Delta z(x,y) = S \times \Delta \varphi,$$

where $S = \frac{p}{2\pi \times \sin(\alpha)} = \frac{p_a}{2\pi \times \tan(\alpha)}$ and

$$\Delta \varphi = \varphi_{\text{object}} - \varphi_{\text{reference}}. \quad (3)$$

### 2.2 Assessment to the phase

Since the grating's period changes with the angle of the projection, the use of a space-frequency methodology is needed and the wavelet's analysis has been chosen [3]. It consists in a temporal signal decomposition based on a “mother” function, the wavelet, which is translated and expanded. The chosen “mother” wavelet has two dimensions: a Morlet wavelet in the perpendicular axis to the projected fringes and a gaussian in the parallel axis to the fringes (Fig 2). Such a wavelet constitutes an adaptative frequency filter in one direction and an average filter in the other. The modulus of the wavelet function is calculated for each analyzed point $\vec{b} = (b_x, b_y)$ and each scale $s$.

To calculate the instantaneous phase of the signal with the wavelet transform (WT), the maximum value of the modulus for each column is determined and the corresponding phase is extracted in the argument of the phase transform [4].

$$\varphi(s, \vec{b}) = \arctan \left( \frac{\text{Im}[\text{WT}(s, \vec{b})]}{\text{Re}[\text{WT}(s, \vec{b})]} \right) \quad (4)$$

Fig 2: Example of the 2D-wavelet, a type shirp signal, and the modulus of the WT of the signal.

The resulting phase is wrapped, i.e. lies in $[0, 2\pi]$. Phase unwrapping is the process of recovering the actual phase values from the wrapped phase data, which is known to be a difficult issue. However the surfaces are here quite continuous and the use of a simple technique based on a one-dimensional method called line unwrapping has been considered as sufficient.

### 2.3 From phase difference to deflection measurement

In practice, an offset can be introduced to account for small variations to the model, changing equation 3. The formula binding phase difference and height for each pixel becomes:

$$\Delta z(x,y) = K_{(x,y)} \Delta \varphi(x,y) + \text{Offset}_{(x,y)} \quad (5)$$

where $K$ and $\text{Offset}$ are determined by regression during calibration. The calibration procedure consists in applying a known translation to a plane object and to calculate the phase maps from which the parameters are deduced. The relation between $\Delta \varphi$ and $\Delta z$ is
better approximated by a three-order regression for bigger displacements. On a classical pavement, the maximum deflection is generally less than 1mm.

An experiment was conducted in laboratory to qualify our methodology. The error between the calculated displacements and the imposed displacement was in any case less than 20µm in a range of 4cm [4]. The measurement sensitivity for deflection is 10µm.

3 The deflection issue

Modelisation analyses have been conducted to evaluate the influence of damages such as interface delamination or cracks on deflection basin.

3.1 Description of the damaged structure

The studied road’s structure consists in an asphalt concrete (AC) wearing course (0.08m; 5400MPa), a road base of bituminous bound granular mixtures (BBGM; 0.15m; 9300MPa) over a sub-base of cement bound granular mixtures (CBGM; 0.21m; 23,000MPa). The structure lays on an infinite pavement foundation of unbound mixtures (UM; 50MPa). Materials are considered as elastic linear. Two damage modes can be found: Transversal cracking of the sub-base can progress through the bituminous layers. Fine cracks can be then observed at the surface.

Such a roadway is designed to support 20 years medium traffic. The sub-base layer is subject to most stress and becomes damaged by fatigue. Sliding takes place at the interface between base and sub-base layers. In the presence of a bond failure interface, the roadway lifetime can be reduced to 5 years [5].

Fig 3: Description of the structure. Left: thickness and material characteristic. Right: position of the different defects

3.2 Numerical studies

Numerical models use 3D finite elements to include either a 1 meter long delamination or a vertical crack in the sub-base layer and optionally in the base layer. Generalized Coulomb friction models the delamination. A small void (1 mm width) models the vertical crack.

Fig 4: left: Values of the radius of curvature under the center of a moving load on a structure presenting a 2m delamination zone (Suvuth, 2006). middle and right: The deflection basins calculated close to the crack for different position of the load, according to the crack position (middle) and according to the load position (right)
Savuth [5] models the effect of a standard dual-wheel running on this structure. He deduced from the successive deflection basins the evaluation of several parameters. Figure 4 (on the left) illustrates the variation of radius of curvature calculated close to the maximum deflection. Its value is reduced by 35 percent when the load is over the delamination. On the middle and the right of figure 4, deflection basins are presented. Crack crosses only trough the CBGM (solid line) or crosses trough CBGM and BBGM (dotted line) on the middle of the figure 4. For a given load position, deflection basins are similar. On the right, crack crosses the 2 layers and deflection basins for 3 distances between load and crack (2m, 1m and 0.1 m) are compared. Maximum deflection increases of 17 % close to the crack. however, variation of radius of curvature (70 %) and of deflection slope at 0.2m of the load (78%) are more important.

3.3 Conclusion about damages
Deflection basin is sensitive to local damages such as delamination or vertical cracking. There are several situations where maximum deflection is not sufficient to describe road's failures or detect damages. Especially to detect such local damages, the measurement sampling has to be adapted. This is why localization of delamination limits or vertical cracks requires a continuous measurement of deflection basins.

4 Application to non-destructive deflection measurements
The experiment was conducted on the pavement fatigue carrousel of the Nantes LCPC (Fig. 5 left). The LCPC pavement fatigue carrousel is an accelerated pavement test facility for the study of full-scale experimental pavements submitted to heavy traffic levels.

The sensor was located on a 2.5m arm to have a fixation independent from the loading. A picture of the sensor is presented on the middle of figure 5. An image taken by the camera with the projected grating is on the right of figure 5.

A reference image was taken at a non loaded state. In this experiment, the images size was 20x27cm² and the shape of the transversal deflection was studied at about 60 to 90cm from the maximal loading. Images were recorded at 10Hz with the camera when the carrousel was operating at about 4.3km/h. For each acquisition, the displacement of the observed area is computed by comparison with the reference image and the mean displacement is calculated.

A complete displacement map is presented on the right of figure 6 for the acquisition corresponding to the maximum deflection (when the loaded wheel is the closest to the sensor).
Fig 6: Left: Mean image displacement in µm for two rotations of the carrousel arm. The first passage is in black and the second passage in dashed grey. Right: Image displacement corresponding to the maximal displacement (maximal load). The scale in grey level represents the deflexion in µm. The load is on the right side. A transversal deflexion profile is presented on the left of the Fig 6. The shape of the profile could be surprising compared to classical results. This is due to the localisation of the observed area, which is at more than 60cm from the wheel axis (Fig. 7, left). A measurement was made at 65cm of the wheel axis with a Benkelman beam and the result (120µm) is in accordance with our methodology.

Fig 7: Left: Localisation of the observed area compared to the transversal deflection curve. Right: Example of transversal profile (rough data in dashed grey and fitted data in black).

The use of a vision technology like fringe projection enables a continuous and full view approach. Different informations could be extracted from the images of displacements like the slope at different distance from the loading and the radius of curvature. These parameters are precisely the ones presented in the numerical study, which shows the pertinence of the imaging technique.

5 Conclusions

Deflection basin is sensitive to damages. The level of maximum deflection is thus modified, but variations are more important for radius of curvature and for deflection slope at a fixed distance from the load. To detect, locate and identify such damages, the deflection basin has to be measured in a continuous way. Based on imaging methodology, a new way to measure the deflection area has been explored. First applications show interesting results, which validate the choice of measuring deflection basin with fringe projection. However, this technique needs to be improved in order to obtain an operational device. An ongoing project aims to concept a support beam to mount the system on a heavy truck.
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References