

Structural roadway assessment using the Frequency Response Function

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Abstract

A shock applied to a road structure generates different physical phenomena according to the characteristic of the shock (frequency, intensity). Thus, deflection is measured when the load is applied by a FWD while compression wave velocities are estimated when the impact echo method is applied. With an intermediate solicitation, surface road vibrations can be measured and the Frequency Response Function (FRF) can be evaluated. This function is sensitive to the presence of internal damage such as voids or cracks. So, the method could be used to detect and locate them. Yet, the sensitive frequency band depends on the investigated structure, that's why a specific process has been developed to standardize the test results. In this way, a road structure mapping can be presented.

Résumé

Un choc appliqué à une structure routière produit des phénomènes physiques différents selon la nature du choc (fréquence, intensité). Ainsi, une déflexion est mesurée sous la charge d'un FWD tandis que la vitesse des ondes de compression est estimée en appliquant la méthode impact écho. Une sollicitation intermédiaire provoque des vibrations mesurables en surface de la chaussée qui permettent d'estimer la fonction de réponse en fréquence (FRF). Cette fonction est sensible à la présence des dommages internes tels que des vides ou des fissures. La méthode a ainsi pu être utilisée pour détecter et localiser ces défauts. Cependant, la bande de fréquences sensibles dépend de la structure étudiée. C'est pourquoi un processus spécifique a été développé pour normaliser les résultats d'essai. De cette façon, une cartographie de la structure de la route peut être présentée.

Keywords

Pavement, Damage, NDT testing, Impulse response, Normalization,

1 Introduction

Roadways are layered structure which needed structural maintenance. Thicknesses and stiffnesses of the different layers could be estimated using GPR results and deflection measurement. Internal damages such as cracks or delaminated interface are difficult to detect and locate. Yet, there are basic information to define the rehabilitation maintenance; frequency response function is a NDT method to improve the structural assessment of roadways.

2 Principle of the method for pavement investigation

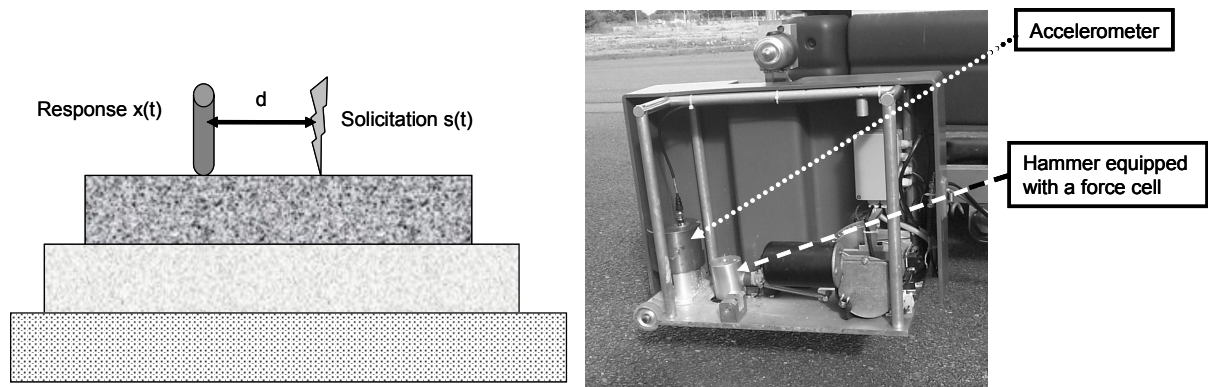
2.1 Principle of the method

The principle of the method (Fig.1left) consists in applying dynamic solicitation on pavement surface, $s(t)$, and measuring the surface response, $x(t)$, at a fixed distance, d closed to the solicitation. The Frequency Response Function (FRF) between response and solicitation is then calculated. Then, this elementary test is renewed as needed at different locations of the roadway section according to the sounding objectives.

In practice, the applied solicitation is usually a shock which allows covering a broad frequency range with a short time solicitation. Vertical acceleration at the road surface is measured to estimate the dynamic response of the pavement. Several tests are repeated on the same measurement point to improve the reliability of the frequency analysis results. Colibri prototype (Fig.1, right) applied the method. It applies 3 shocks to the road surface and measures the vertical surface response (vertical acceleration) close to the solicitation (0.10m). It deduces the inertance FRF ($A(f)$) which is the ratio between a harmonic acceleration response and the harmonic force (Ewins, 2000). Colibri could be manually moved or mounted behind a vehicle which allows adapting the distance between testing points.

For a healthy structure, the shock generates vibrations of the whole pavement. Frequency response will be amplified starting from the first Eigen (or natural) frequency. Damages lead to softening the structure, and thus reducing the first Eigen frequency. This low frequency vibration mode corresponds to the vibration of a part of the structure (for instance above a delamination). The inertance FRF of the damaged structure is higher than the one of the healthy structure in a specific frequency band.

The method consists in defining a reference inertance FRF representative of the healthy structure, detecting the inertance FRF higher than the reference one and observing their frequency band affected by damages.



2.1.1.1.1 On the left: principle of the method; on the right: Colibri prototype mounted behind a vehicle

2.2 Data processing

For each measurement point, i , a spectral analysis of the several tests leads the calculation of the inertance, $A(f, i)$, and the coherence function, $\gamma(f, i)$, between the pavement response and the applied solicitation. These functions depend on the frequency, f , and on the measurement point. The coherence function estimates the dependence of the output signal compared to the input signal. It is a real value ranging between 0 (no dependence) and 1 (full dependence). A minimum threshold of coherence (usually 0.8) is chosen to validate or not the calculation of the inertance. This threshold can be adapted according to the studies. For each frequency and each measurement point, FRF is validated if the coherence value is higher than

this threshold. Thereafter, the analysis is restricted to the population of validated measurements.

In a homogeneous zone, according to the road data base, measurement results are processed in 2 steps:

- Estimation of a reference function representative of the healthy structure;
- Calculation of a normalized damage.

2.2.1 Calculation of the reference function representative of the healthy structure

As mentioned early, the FRF measured on each point has to be compared to the one of the healthy structure. Unfortunately, this reference function is usually unknown. The first step consists in building a reference function representative of the healthy structure. We know that this function corresponds to the low level of response. To estimate the reference function modulus, a part of the tests are supposed to be carried out on a healthy zone. This could be done voluntarily by investigating an un-trafficked zone such as an emergency lane. In practice the set of modulus, $|A(f_k, i)|$, measured at a fixed frequency, f_k is considered. The reference value at this frequency, $|A_{réf}(f_k)|$, is defined as a percentile of selected population. The percentile 20, which allows obtaining a low value representative of the healthy structure and eliminating abnormal measurements, is usually adopted. The set of reference values are used to build the reference transfer function representative of the healthy structure, $|A_{réf}(f)|$.

2.2.2 Calculation of a normalized damage

Inertance modulus increases with frequency. The FRF modulus, $|A(f_k, i)|$ are normalized using the modulus of the reference function. For each frequency and each measurement point, the damage, $D(f_k, i)$ is calculated (Eq. 1). This value is contained between 0 and 1. The matrix D represents the damage on the road section for the different frequencies. It can be presented as a damage mapping where:

- X-coordinate is the abscissa along the road section;
- Y-coordinate is the frequency band;
- Colors represent the level of damage.

$$D(f_k, i) = \begin{cases} 0 & \text{si } |A(f_k, i)| < |A_{réf}(f_k)| \\ 1 - \frac{|A_{réf}(f_k)|}{|A(f_k, i)|} & \end{cases} \quad (1)$$

3 Application on test sites

3.1 Detection of interface defect

A test site has been investigated using Colibri prototype. Its structure includes 4 layers: A wearing course 0.06m thick, 2 BBGM layers 0.10m thick and unbound granular mixtures (UGM) 0.20m thick. The structure includes 2 pieces of Kraft paper (0.5 x 0.5 m) which represent interface defects. One is placed at the AC/BBGM interface; the second is located at the interface between the 2 BBGM layers. Figure 2 presents the image applying the dynamic investigation method. The theoretical localization of the defects is indicated on the graph. Frequency band between 3000 and 5500Hz is sensitive to the interface defects. The first one (nearer to surface), is easier to locate because the stiffness contrast between the healthy

structure and the substructure located above the defect is high. Its localization is good. The deeper defect is less readable because the structure under the defect is soft.

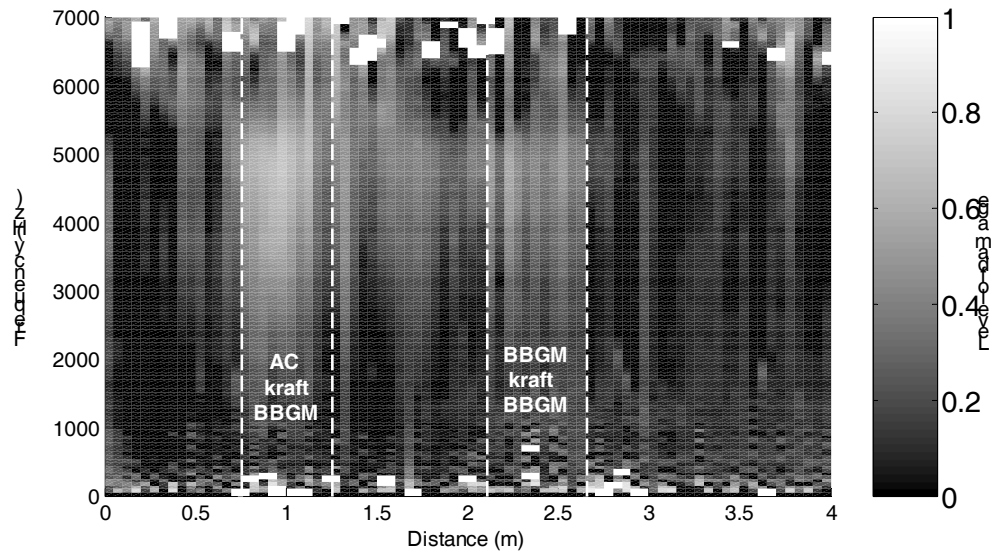


Figure 2. Damage image deduced from the dynamic investigation of a test site with interface defects.

3.2 Detection and evolution of reflective cracking

Dynamic investigation is based on variations of the structure softness. Vertical cracks represent variations of limit conditions which reduce the Eigen frequencies. They can also be detected with dynamic investigation. The technique has been used during an experiment which tests different technologies to limit reflective cracking.

A concrete structure was sawed. Different anti reflective cracking processes were used before covering the structures with a 0.06m thick AC wearing course. Pavement fatigue machines applied a load 1 M times above each crack. Load is a standard 65kN dual-wheel running at 2m/s. Dynamic investigation has been conducted at the beginning and at the end of the experiment. It extended 0.5m on each side of cracks in 3 longitudinal profiles: under each wheel path (noted north and south) and between the 2 wheels path (noted center). Intervals between consecutive measurements were only 0.02m near a crack (<0.20m) and 0.05m at father distance. Pavement sounding was held over one half-day under homogeneous and constant operating conditions. An unloaded zone has been investigated to evaluate the influence of climatic conditions on measurements.

Each longitudinal profile has been independently processed and compared to the reference functions. Results from the unloaded zone showed any influence of climatic conditions. On the other hand, some differences are observed on the reference functions deduced from 2 anti-reflective cracking techniques before fatigue testing. The stiffness of this component influenced the FRF measured. So a reference function has been defined for each anti-reflective technique.

Using the reference function, the damage matrix has been calculated for each crack at the beginning and the end of the fatigue test. Figure 3 shows example of the images deduced from dynamic investigation before and after fatigue testing. Crack is located at the null abscissa. Its influence is readable before and after fatigue testing in a wide frequency range. Before fatigue testing, the crack influences the results at a distance lower than 0.2 m. During fatigue testing, the crack grows up trough the anti-reflective system and trough a part of the wearing course. That is why image after the fatigue testing is influenced in a longer zone.

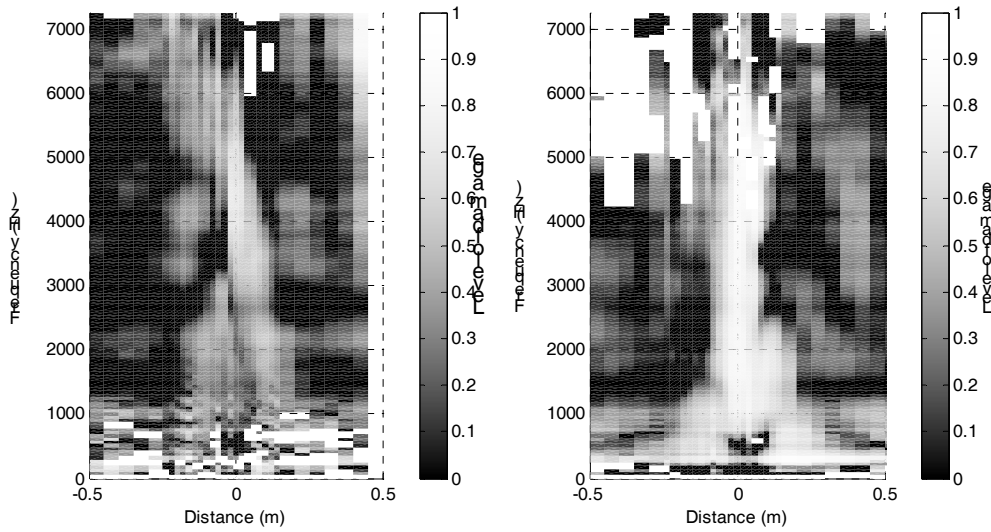
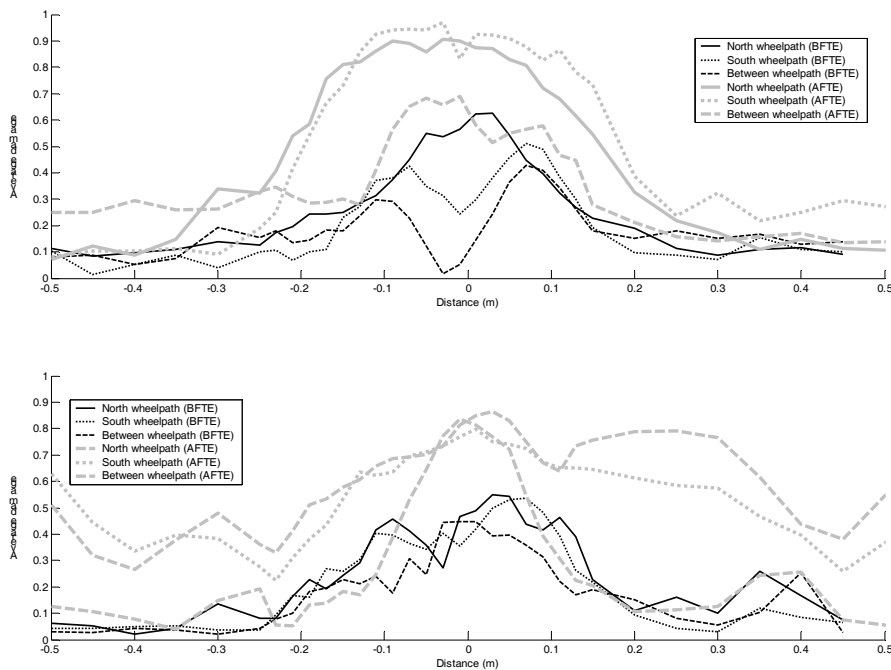


Figure 3. Images of estimated damage over a crack between the wheel-path; before fatigue testing (on the left); after fatigue testing (on the right)



3.2.1.1.1 Average damage in the frequency range 1 500 – 5 000 Hz estimated by Colibri on the various profiles before (initial) and after (final) fatigue testing; Reference technique(at the top) and alternative technique (at the bottom)

Then, a damage index has been calculated for each measurement point. It was equal to the average of the individual damages estimated in the frequency range 1500–5000Hz. Comparing damage indexes profiles is easier than comparing several images. Figure 4

presents the index variation along the 6 profiles for the reference construction technique and for an alternative construction technique.

Before fatigue testing small differences exist in the longitudinal profiles which correspond to transversal dispersion of the test site. Damage level increases up to 0.5 close to the crack. It influences dynamic results only at a short distance (<0.2 m).

After fatigue testing, the damage index increases. It is different under each wheel path and between the 2 wheels path. For the reference technique, the index goes up to 1 under the wheel paths while between the wheels path, it increases only up to 0.7. The index decreases to match the initial level at a distance of 0.3 to 0.4m. For the alternative technique, the index increases up to 0.9 between the wheels path close to the crack. Under the wheel paths, the index is always higher than the initial level.

Visual inspection in situ and destructive testing (Perez, 2008) show us that the bond between asphalt wearing course and concrete failed under the wheel paths with the alternative technique while the interface was always bonded for the reference technique.

Dynamic investigation gives us a non-destructive technique to follow up the spread of reflective cracking and the interface bonding. It also allows calculating an objective index to compare different rehabilitation techniques.

4 Conclusions

Dynamic investigation is a method to detect stiffness variation of structure. In the context, of pavement sounding, damage presences such as unbonded interface, delamination or inside cracks, reduce pavement stiffness. So, these damages can be detected with this method. To adapt the method, a data process has been defined to build a reference frequency response function representative of the healthy structure. Then, it is used to normalize individual results. A mapping of the results could be used to locate the defect and to define the affected frequency range. Finally, a synthetic index can be estimated and used to follow up the crack growing or the delamination extension by time or traffic.

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