Dynamic Investigation of Pavements

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ABSTRACT: The design of pavement structures is usually carried out under the assumption of bonded interfaces between the various layers. However, interface defects exist leading to a different stress diagram, which reduces the bearing capacity of the roadway. Mechanical impacts in a broad range of frequencies, give different responses according to the presence or the absence of defect. According to the intensity and the frequency of the impact, the physical phenomena differ, leading to different measurement and data processing. The paper presents different experiments using impacts on test sites, and compares the practice of these methods. It illustrates the problem of the coupling between the sensor and pavement surface to sound. It also compares the results of the method in different frequencies ranges.

KEY WORDS: Impact-Echo, transfer function, pavement, sounding, interface flaw

1 INTRODUCTION

The design of pavement structures is usually carried out under the assumption of bonded interfaces between the various layers (LCPC-SETRA, 1997). However, interface defects exist leading to a different stress diagram, which reduces the bearing capacity of the roadway.

The detection and the characterization of sliding interface can be done by destructive or non-destructive methods. Among the latter, mechanical impacts in a broad frequencies spectrum, give different responses according to the presence or the absence of defect. According to the intensity and the frequency of the impact, the physical phenomena differ leading to different measurement and data processing:

- Heavy low frequency or static load lead to measure the deflection or the radius of curvature;
- Impact in the frequency range 100 Hz - 7 kHz implies to measure modal vibration at road surface (Bats-Villard, 1991);
- Impact in the frequency range 3 - 30 kHz induces to propagate mechanical waves and to measure frequency resonances by the Impact-Echo method (Sansalone, 1997).

In the two last cases, an impact (possibly measured) is applied to the road surface and the vertical acceleration is measured on the surface near the impact. The paper presents different experiments using impacts on test sites, and compares the practice of these methods.

2 THEORICAL ELEMENTS OF THE METHODS

2.1 Impact-Echo method

Impact-Echo is based on the use of impact generated stress (compression) waves that propagate trough structures and are reflected by flaws or interfaces between layers of different density or elastic moduli. Surface displacements (acceleration) caused by reflections of these waves are recorded by a transducer close to the impact. This displacement is transformed into the frequency domain. Multiple reflections of stress waves between surface, flaws and/or interface give rise to transient resonances, which can be identified in the spectrum. These frequency peaks are used to evaluate the integrity of the structure, and can provide layer thickness or flaw depth measurements.

Impact-Echo applied onto a layered structure (like roadways) is characterized by multiple reflections of the compression wave at the different interfaces. Let's consider a structure consisting of two layers of thicknesses T1 and T2, with acoustic impedances Z1 and Z2 ($Z = \rho . V_p$, ρ: Density, V_p: Celerity of compression waves). Waves propagate trough layer 1 and are reflected and refracted at the interface. According to the acoustic impedance difference, the phase of the reflected wave changes or not. So waves arriving on surface are always tension waves or alternately compression and tension waves. The refracted waves propagate trough layer 2, are reflected off the lower interface and come back to the structure. Figure 1 shows on the left side, waves propagation trough the 2 layers; on the right side, a wave is reflected off the interface when Z1<Z2.

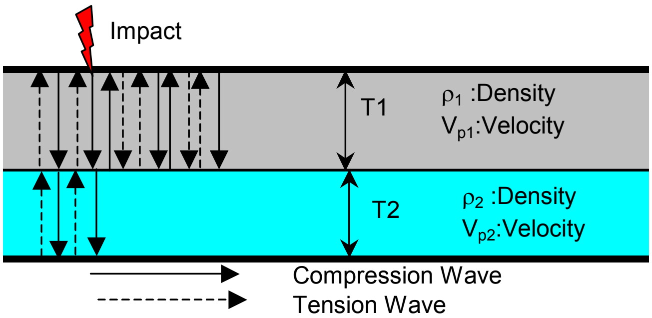


Figure 1: Waves propagation in a 2 layer structure (Z1<Z2)

Frequency analysis of the surface displacement allows detecting different frequency peaks summarized into the table 1.

Table 1: Equations of Impact-Echo frequency according to the acoustic impedance

Impact-Echo frequency	Z1>Z2	Z1<Z2
For the first layer	$f_{IE} = \beta_1 \frac{V_{P1}}{2T_1}$ (Equation 1)	$f_{IE} = \frac{V_{P1}}{4T_1}$ (Equation 2)
For the 2 layers	$f_{IE} = \frac{1}{\frac{2T_1}{\beta_1 V_{P1}} + \frac{2T_2}{\beta_2 V_{P2}}}$ (Equation 3)	

The β factor depends on the interface conditions for the first layer. It is equal to 1 when the interface is bonded, but it is reduced when a flaw exists. The β factor is also dependant of the material properties. For concrete, Gibson showed that it vary from 0.945 to 0.957 for a Poisson's ratio varying from 0.25 to 0.16 (Gibson, 2005).

2.2 Modal testing

When an interface flaw exists between two layers, the impact response of the structure could be fundamentally different from the one of the sound structure. Flexural modes of vibration could be excited by the impact and the part of the structure above the flaw vibrates. The flexural modes frequencies are lower than the Impact-Echo frequency. The former depend of the shape and the depth of the flaw, the material properties and the boundary conditions. Table 2 gives the five lowest frequencies calculated for a bituminous plate with different shapes and different boundary conditions.

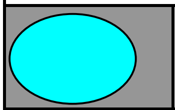
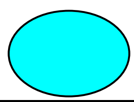
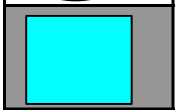
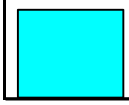
Mode		1	2	3	4	5
	Clamped disc	577	1200	1971	2250	5030
	Free disc	297	514	692	1161	1994
	Clamped square	507	1034	1526	1855	1864
	Free square	199	290	337	507	868

Table 2:Example of flexural vibrating mode frequencies for different shapes and boundary conditions

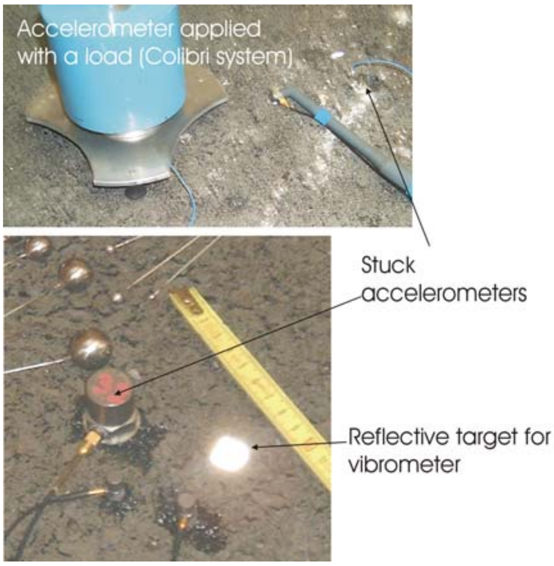
3 PRACTICE OF THE METHODS

The sounding by mechanical impact poses two major problems: Control of the impact and measurement of the vertical displacement at the road surface. Table 3 gives illustrations of various systems of impact and measurement of the response on the surface used during our experiments.

The set of 10 spherical steel impactors allows applying impacts with various frequency spectra to the structure. The smaller is the ball, the higher is the frequency spectrum. A good experiment is required to obtain a repeatable impact. The two hammers include a force cell, which makes it possible to record the force applied. The surface of contact is more significant than with the balls system. The Colibri hammer is mechanized, which makes it possible to control the impact in amplitude, and to obtain a repeatable test. Moreover it allows to control the impact position with respect to the measurement device. It should be noted that on roadway, and particularly on asphalt surface, the impact position, either on an aggregate or on the binder, could significantly influence the impact spectrum.

To measure the surface response, accelerometers are usually used. However, it is necessary to ensure a good coupling between the structure and the sensor. So, the sensor can be stuck on the structure, but the test duration is longer. To reduce this duration the accelerometer can be applied on the structure with a load. In this case the frequency band, which can be analyzed, is reduced. A laser vibrometer is useful to solve the coupling problem, however, reflective system could be necessary to make the sensor work properly.

Table 3: Various impact systems and surface response measurement devices.

Different impact systems	Measure surface displacement devices
  	

4 TRIALS ON BITUMEN TEST SITE

Trials were carried out on two asphalt test sites both made of a layer of 25 cm bitumen-bound granular material, covered with a layer of 5 cm bituminous concrete. The formers interface was well bound while the latter's was degraded by placing a polyamide film between the two layers. Trials used 2 hammers with force cell. The surface response was measured with 2 identical accelerometers. A first series of tests was done with 2 stuck accelerometers. For the second series one accelerometer was stuck while the other was applied using the Colibri system (figure 2).

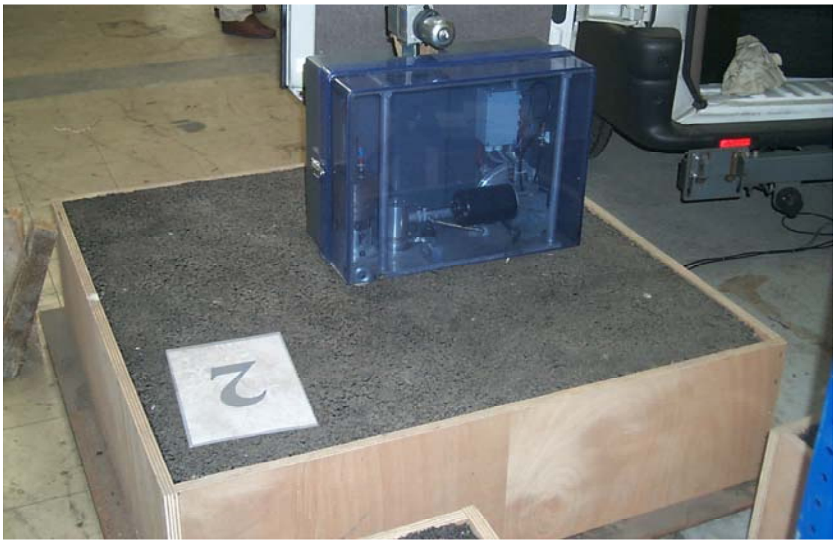


Figure 2: The Colibri system on the asphalt test site

Using the stuck accelerometer signal as a reference, we calculated the transfer function. It is equal to the ratio of the crossed spectrum of the 2 signals to the power spectrum of the reference signal. In this paper only the module of this complex function is considered.

Figure 3 compares both series of tests. Each colour represents 3 tests with the same hammer on the same test site.

The upper graph shows the module of the transfer function when the 2 accelerometers are stuck. The module is worth around one unit but not always equal to the unit, which represents response differences. We verified that for frequencies lower than 10 kHz, the coherence between the 2 signals was very good (>95 %). So, the response differences come from the behaviour of the test sites. The distance between both accelerometers was 10 cm long.

The lower graph shows the module of the transfer function when only one accelerometer is stuck. We verified that for frequencies lower than 10 kHz the coherence between the 2 signals was very good (>95 %). However, the module of the transfer function increases for frequencies higher than 6 kHz. These experiments showed that the Colibri system could be used only for frequency analysis lower than 6 kHz.

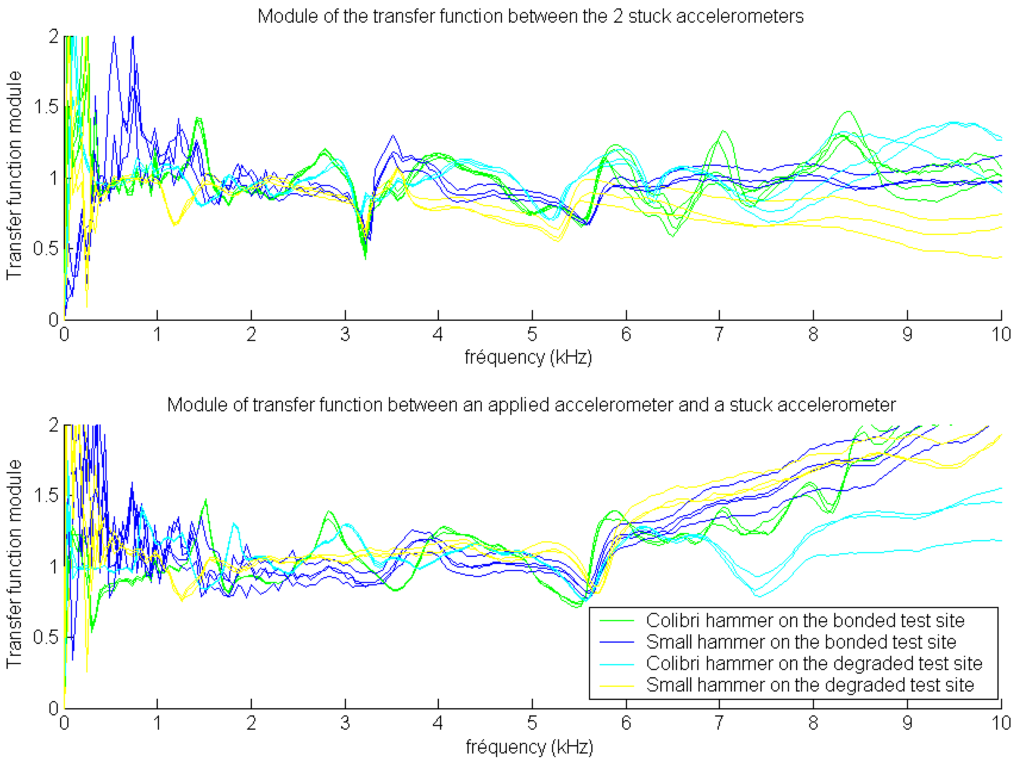


Figure 3: Transfer function modules between 2 stuck accelerometers and one load applied and one stuck accelerometer using different hammers on the 2 bituminous test sites.

On each test site, 9 trials were carried out with various hammer drop heights with the Colibri system. Figure 4 presents the module of the transfer function, and the coherence function between accelerometer and cell force signals. It is observed that up to 6 kHz, coherence is higher than 0.8. Beyond this frequency, coherence is falling, thus prohibiting the exploitation of measurements. The curves of module of the transfer function on the two test sites constitute two distinct spindles on the frequency band 0.2... 6 kHz. On the latter, the Colibri system makes a sensitive difference between the two test sites.

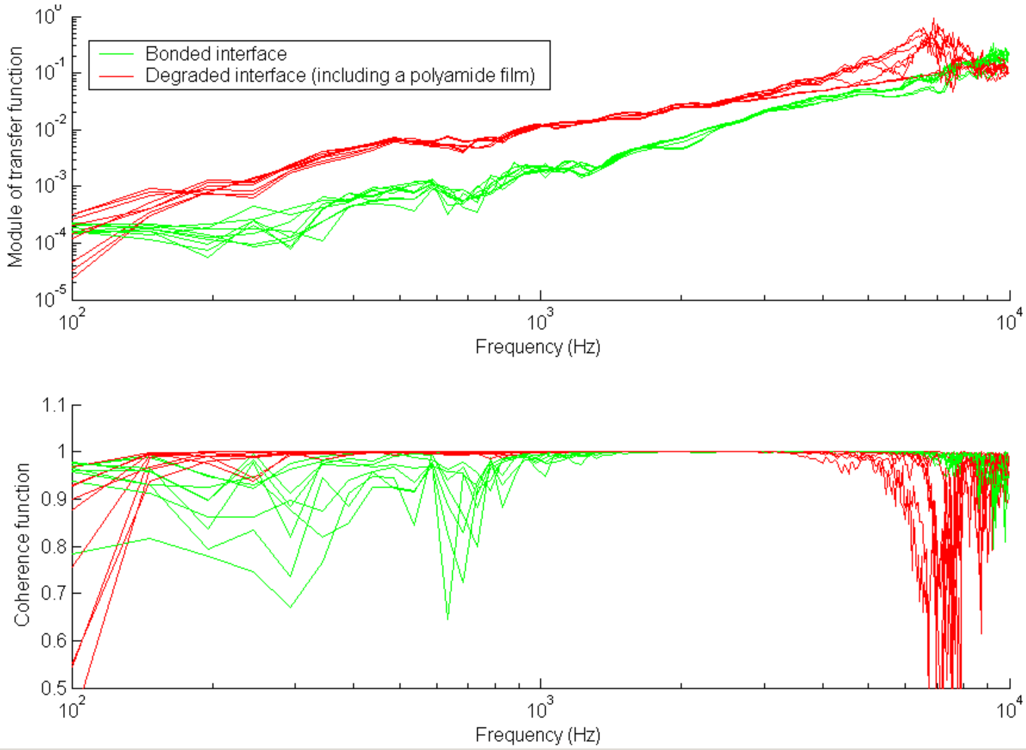


Figure 4: Module transfer function and coherence function on the test sites (Colibri system).

5 TRIALS ON CONCRETE STRUCTURE

5.1 Test site trials

A test site was built to study the cement concrete joining on bitumen materials (Pouteau, 2005). A 17 cm continuous reinforced concrete structure was built on an old wearing course of which few centimeters were milled. This site is also useful to test various methods of non-destructive testing. For some zones, the concrete slab is bonded on the bituminous layer, while the others are laying on a polyamide film as shown on figure 5. Measurements were done on this site with the Colibri system as well as other devices to test the Impact-Echo method. The latter used a small instrumented hammer and stuck accelerometers to points of surface, noted A and F on figure 5. Applied force and resulting acceleration were measured and recorded in order to analyze first the accelerometer signal alone, then the transfer function between acceleration and force.

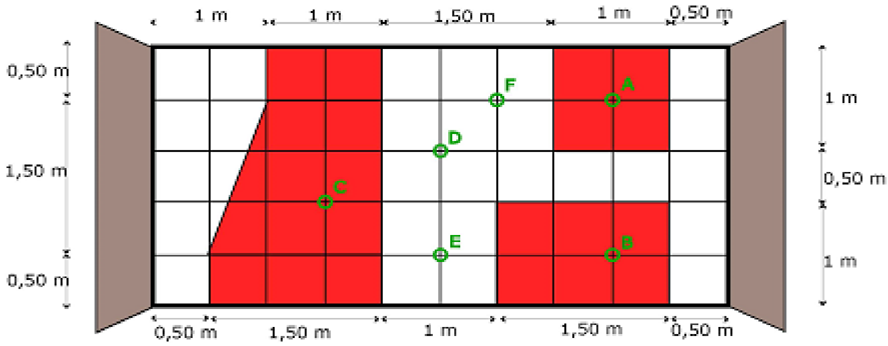


Figure 5: Map of the bonded and degraded zones on the test site (Pouteau, 2005)

The method Impact-Echo applied to the test site can yield to two observable frequencies relating to the thickness of concrete according to whether the waves are reflected off the interface with or without phase shift. The first frequency is obtained by applying the equation (1) in the case of a sliding interface. In the case of a bonded interface, the frequency is then given by the equation (2). With a speed of 4400 m/s, this yield to frequencies of 12.4 or 6.5 kHz.

Figures 6 and 7 present the time-frequency analysis of the signals. The lower graph presents the temporal signal (in blue) and the Hanning windows used for the frequency analysis. The left hand graph presents the Fourier transform module of the whole signal. The third graph presents the time-frequency analysis. On both figures, one observes that after the initial shock, a phenomenon corresponding to the Impact-Echo one is persistent. The frequencies deduced from the test are 6.49 kHz in the bonded case, and 12.21 kHz in the degraded case.

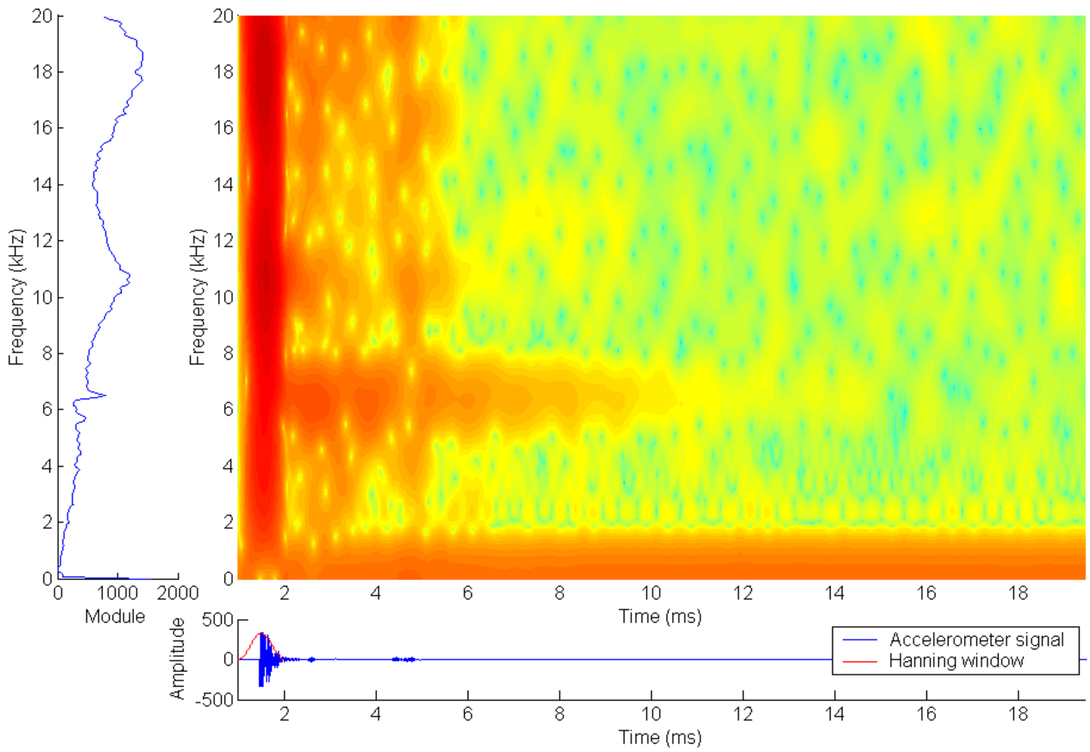


Figure 6: Time-frequency diagram obtained on the bonded point (F) by applying the Impact-Echo method.

To supplement the analysis, coherence and transfer functions were calculated using the hammer force cell signal. Figure 8 shows the results for 2 tests carried out symmetrically around points A and F. It is observed that the results are coherent between 4 and 16 kHz. In this frequency band, the transfer function module:

- Remains virtually identical for both points of measurement up to 11 kHz;
- Presents a peak for the tests on the degraded point at the Impact-Echo frequency;
- Is nearly the same for both measurements points though sensitively distinct up to 16 kHz.

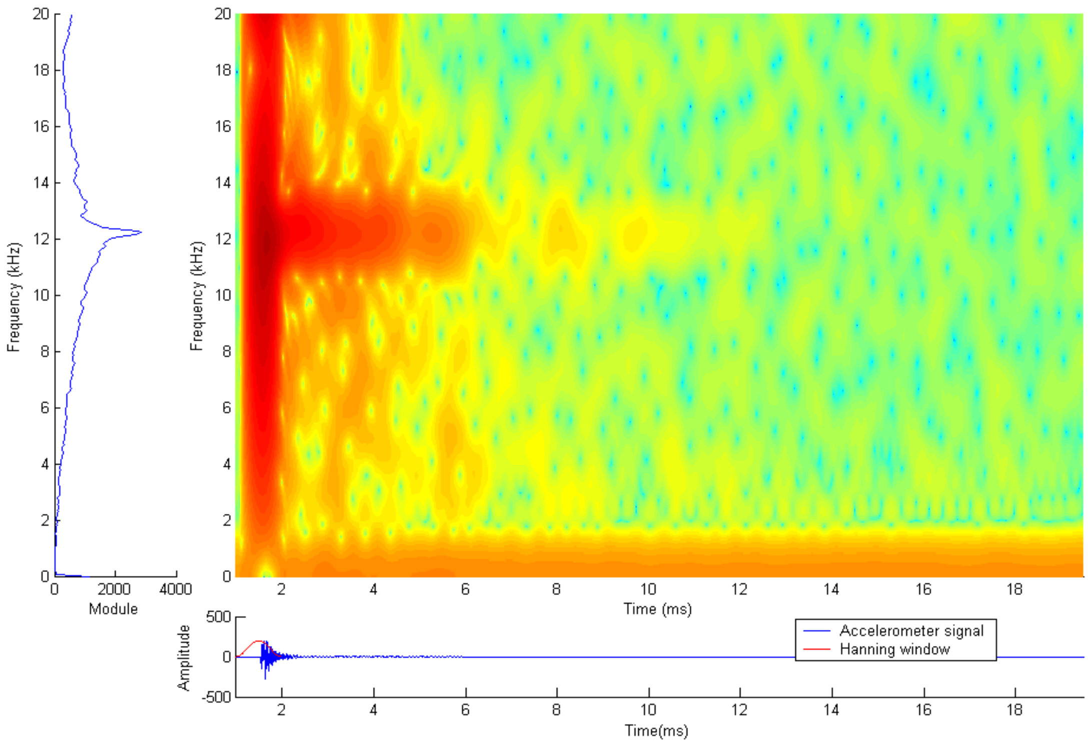


Figure 7: Time frequency diagram obtained on the degraded interface (A) by applying the Impact-Echo method.

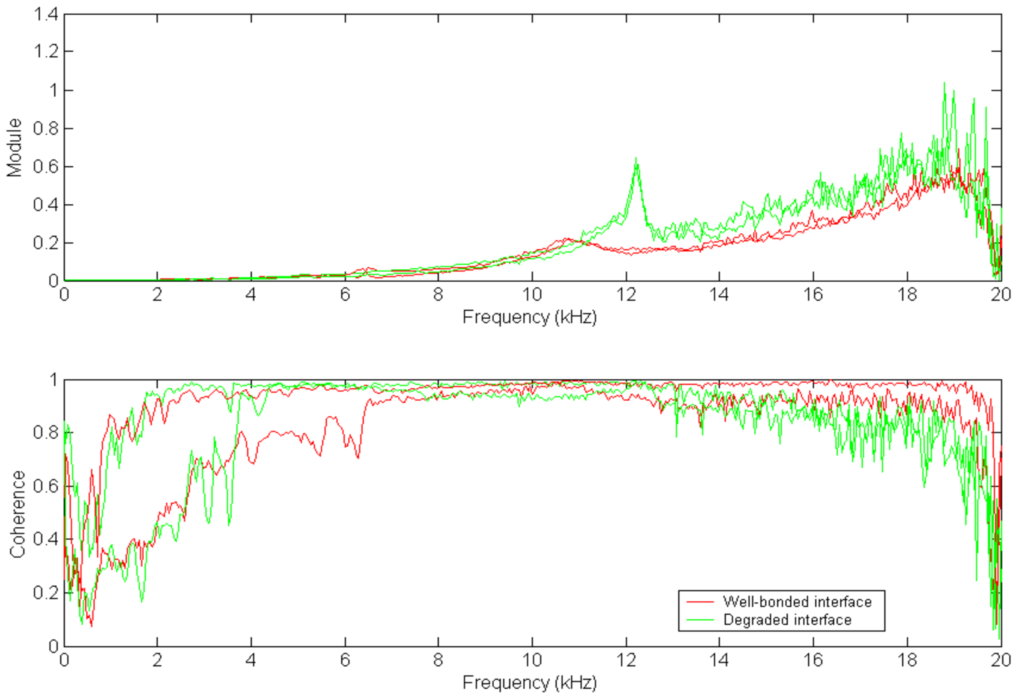


Figure 8: Transfer function module and coherence function calculated for various tests at bonded and degraded points of the test site.

5.2 In situ trials

A similar structure was implemented on a circulated roadway. It is made of 17 cm continuous reinforced concrete laying on a bitumen bound granular material. A very thin asphalt-surfacing layer covers the whole. On an experimental zone of this roadway a polyamide film has been put between the concrete and the bitumen layers to simulate a degraded interface. The polyamide film is 4 meters long and extends all across the transverse road profile. For safety reasons, only the Colibri system has been used to follow the potential propagation of this interface defect. The tests were carried out along the road. It began 2 meters before polyamide zone and ended 2 meters after it. The distance between two consecutive measurements varies between 5 and 20 cm, intervals being reduced near the polyamide limits.

Measurements realized with Colibri allow to calculate coherence and transfer functions between acceleration and the applied force. It is observed that the bonded and degraded interfaces yield to transfer function modules significantly different on a broad frequencies range. A synthetic indicator can be calculated to integrate this frequency band. However, this poses the problem of the weight to be given to each frequency. In order to overcome this difficulty, the transfer function modules were normed for each frequency on the maximum value obtained for the whole of the measurements at this frequency. This maximum value corresponds to a degraded point. Figure 9 shows the result obtained with the tested pavement structure. The polyamide limits can be easily seen in the frequency band 1... 5 kHz.

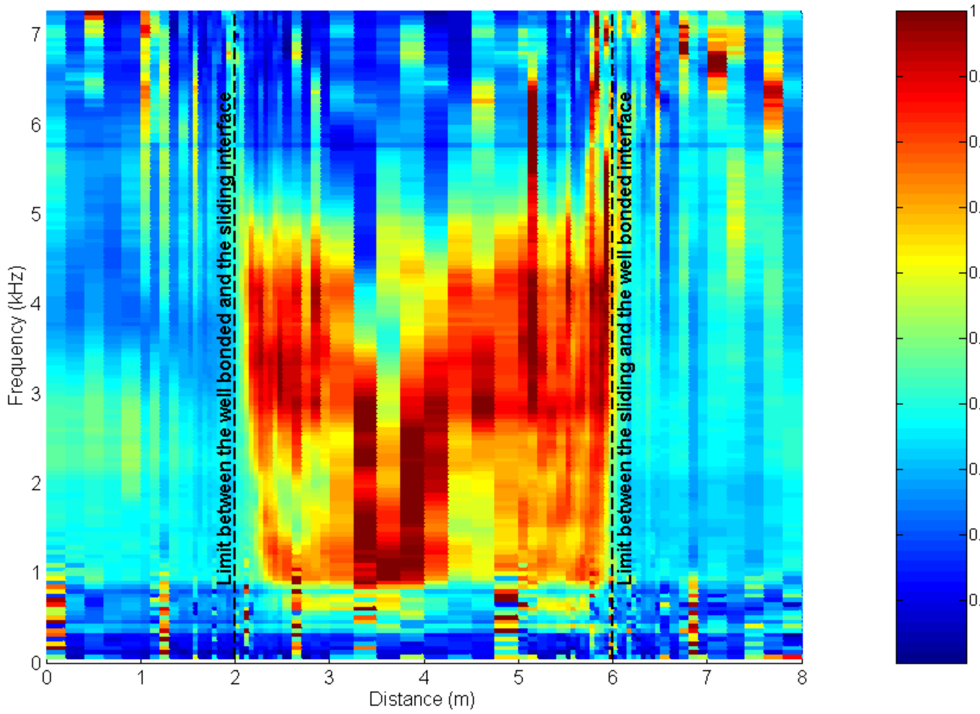


Figure 9: Transfer function normed for each frequency obtained from Colibri measurements on the continuous reinforced concrete structure.

The experimental in situ tests showed that the Colibri system is suitable to determine accurately the interface defect limits for various depths. The significant frequency band depends on the nature of the structure. It is thus preferable to observe the results on a wide range before building a synthetic indicator for the tested structure.

6 CONCLUSIONS AND PROSPECTS

Roadways sounding mechanical impact allows the detection and the characterization of interface defects inside the pavement. According to the frequency range scanned used, devices have to be well chosen. The measurements interpretation must be made in a differentiating way according to the frequency band analyzed.

In the frequency range 100... 7000 Hz, the transfer functions between the surface acceleration and the applied forces can be used. This principle implemented by the Colibri device makes it possible to detect the limits of the defect in its horizontal extension.

In the frequency range 3000...20000 Hz, the method Impact-Echo can be used. Acceleration alone is sufficient and makes it possible to calculate the flaw depth. However, it is better to measure the applied force. Thus, the presence of a defect can be verified.

In practice, the coupling between the sensor and the surface to sound is essential. This limits the operational use of these methods. However, the development of new technology of measurement without contact as the laser vibrometry should allow the development of operational tool in higher frequency range, as well as it should reduce the trials duration.

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REFERENCES

LCPC-SETRA, May 1997, *French Design Manual for Pavement Structures*, Technical Guide, LCPC SETRA

Bats-Villard M., 1991, *Influence des défauts de liaison sur le dimensionnement et le comportement des chaussées*, Thèse de doctorat, Université de Nantes

Sansalone M, Street W.B., 1997, *Impact-Echo, nondestructive concrete of evaluation and masonery*, Cornell University

Gibson A., Popovics J S., April 2005, *A Lamb wave basis for Analysis Impact-Echo*, Journal of Engineering Mechanics, Volume 131, Number 4

Pouteau B, 2004, Durabilité *du collage blanc sur noir dans les chaussées,* Thèse de doctorat, École Centrale et Université de Nantes

Simonin J-M., 2002, Using seismic investigation to test interfaces between two pavement layers, Bearing Capacity of Roads, Railways and Airfields, Volume 1, pp721... 729, ISBN 90 5809 396 4