Vibro-acoustic analysis to detect structural deterioration on roof covering plates

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Abstract

Acoustics is a very broad research field and it can be applied in various science domains.
This article explains a new approach in evaluating the conditions of used coverage plates on a walkable roof, which can become dangerous for the pedestrians.
The assignment from the building owner was aimed at researching and verifying a Non Destructive Test (NDT) method to investigate and identify which elements of the roof coverage were deteriorated.
Instead of visually inspecting thousands of tiles, a new acoustic based investigation methodology has been developed, enabling very good accordance between non visual acoustic measurements and visual control.
Using FFT accurate analysis of a microphone and a tri-axial acclerometer signals, this methodology defined a tiles "Index of Selection" to search for an emitted sound vs. coverage plates status correlation.
An official subjective judgment was provided also by Security Officers and Building Maintenance staff present during the tests, which confirmed the results.
The full roof coverage with more than 10.000 tiles was later completely investigated, confirming the methododology expectations and allowing to change only about 1/3 of the total number of tiles.

1 Introduction

A walkable roof exposed for more than 10 years to different climatic conditions becomes a problem due to the dangerous rupture of several coverage plates (tiles), mounted on supporting bricks over a plenum of about 80 cm.
The problem was the impulsive force generated by a pedestrian walking person (even running in dangerous situations) which was strong enough to make some plates to collapse and to create dangerous conditions up to breaking a leg. The big concern arose by considering the worse case of an alarm evacuation: a situation in which a crowd will run on the mentioned plates to reach escape stairs with a very probable number of people seriously injured, a situation which must be avoided.

Instead of visual inspecting more than 10.000 tiles, the idea was to hit them with a rubber hammer and listen to the sound emitted by the plates, as the human ear can actually notice a different sound emission with a variable timber (tonality in first approach) among plates in normal good conditions and others with some deterioration or damaged conditions.
In this presentation we focus on some results from a preliminary screening on a minimal set of plates in different coverage areas, which has given a significant correlation between subjective and objective results. The follow-up of the present preliminary test was that more than 10.000 plates were then tested and classified with a good statistical correlation with subjective opinions and visual check-up of a sub-ensemble of tiles.
After performing several analysis of the collected audio signal data with different standard frequency analysis techniques, we decided to identify some tonal characteristic correlated either with the visual inspection of individual tiles and with subjective listening judgment by the operators.
The vibro-acoustic preliminary tests were carried out on two areas (GR1 and GR2) consisting of 20 and 15 tiles respectively, which present different ageing conditions and for which a subjective judgment was provided by Security Officers and Building Maintenance staff present during the tests. Figure 1 shows preliminary test on GR1 and GR2 areas.

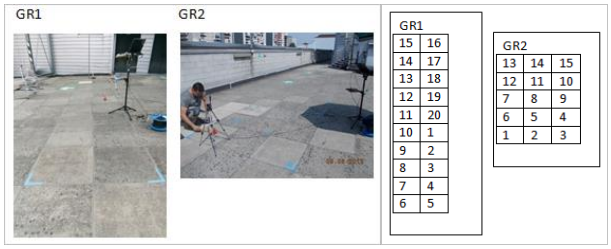

Figure 1. Gr1 and GR2 preliminary tests

2 Data acquisition and processing

2.1 Visual inspection

The tiles have been numbered among GR1 and GR2.
GR1: tile n.15 was new, while the others showed signs of deterioration in various extents although they were not among the worst views.
From a visual examination of the back side, the tiles ranging from number 1 to 5 were worse, in GR2: the n. 6 was broken, tiles number 1, 3, 7 were good, 12 and 14 medium, while the others were more worn.

2.2 Data acquisition and signal analysis

The mechanical excitation of the individual tiles was carried out by means of a rubber hammer and a sequence of manually given pulses, with the aim of energizing the structure without incurring in the tiles wobbling on their support seats and without damaging them.
For each tile the signals of a microphone placed about 30-40 cm above the tile and a tri-axial accelerometer placed in the middle of it were recorded.
The following figure 2 show different FFT sound emission spectra by each single tile beaten with the rubber hammer.

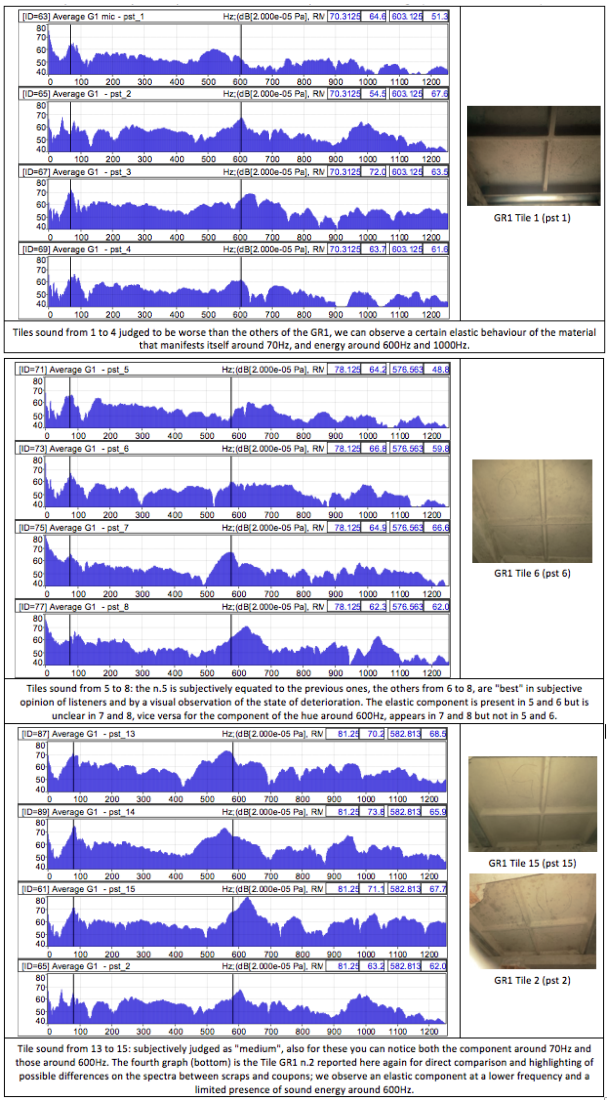

Figure 2: FFT spectral Analysis sound samples emitted by the roof coverage (hammer beaten tiles)

Deriving from first GR1 results tiles group, we developped the idea to focus the research on the frequency "zones" around 70 Hz and 600 Hz. The same analysis was performed on the GR-2 tiles group with similar results, comfirming the methodology correctness and faithfulness.

3 Research for an Index of Selection

On the basis of what was observed, we oriented the search for a Selection Index by approaching the field of the metric related to the sound perception, which in theory means investigating the sensation of the human hearing regardless of the acoustic signals energy content. Prominence Ratio is a particular index derived from sound and vibration analysis techniques originally developed to check for aurally prominent tones in a noisy signal.
PR is formally defined in ANSI S1.13-2005 “Measurement of Sound Pressure Levels in Air” [1] for general use and in ECMA 74 12th Edition 2012 [2].
According to these standards, the prominence ratio is applicable if there are tones pesent in the signal and they represent an objective measure to assess if these tones are “prominent”. A sound is classed as “Prominent” if PR > 9 dB.
Let's recall the different definitions between TNR and PR:
a) the TNR exist when the frequency components called "Tone" has a level which is at least 8 dB higher than the level of the corresponding critical bands expressed in Bark scale,
b) the PR exist when the level of the critical band containing the tone is at least 9dB higher than the level of the adjacent critical bands (masking noise assumed by some authors).
In this field some indexes defining the "Hue" of a sound perception have been defined as TNR (Tone to Noise Ratio) and PR (Prominence Ratio); this approach, in short, deals with two indexes which describe a specific sound sensation and quantify the perceived sensation: for example Hum produced from mosquitoes, transformers, etc. or Whistle produced from fans, Hard disk, tires, etc..
These two indiexes differ in the considered frequency base; the TNR is based on some frequencies bands and the methodology typically starts from an FFT (Fast Fourier transform) analysis, while the PR performs the Barks analysis, a specifically created scale to adapt a frequency analysis of human hearing; briefly, the Bark scale is similar to the 1/3 octave frequency band.
Both indexes rely on the assumption that a tone is only perceived if the level is greater than a certain masking quantity with respect to the remaining noise and take into account the limited capacity of the human ear to distinguish between two sounds very close in frequency (masking effect).
This paper is not aimed at mastering all details and discussions about psycho-acoustics science, but the point is that although the “tone” or assimilated sensation are not visible in this specific sound spectra analysis (Fig.2 above), there still was a sound perception of some tonality.

Making the investigation of the Index of selection research as simple as possible, we wanted to understand if either TNR or PR can be used as an index about the existence of a "kind" of tonality which might classify the tiles as acceptable or damaged, therefore with a residual elasticity around 70 Hz and a characteristic sound emitted in the 600Hz area.
The TNR and PR were evaluated from the preliminary set results of GR1 and GR2 samples tested over a whole frequency interval (20 Hz to 20 kHz) without imposing any frequency or range limitations. We noticed that a correlation between PR (Prominence Ratio) and Visual inspection was present appearing in the 600Hz frequency zone.
The definition of PR regarding the level of a critical band and not of the "tone" level itself can explain why in our case there is a hearable tonality detection without the visible presence of a real pure tone like a single frequency component.
The following Fig. 3 explains the PR concept in the Bark frequency scale (yellow overlay).

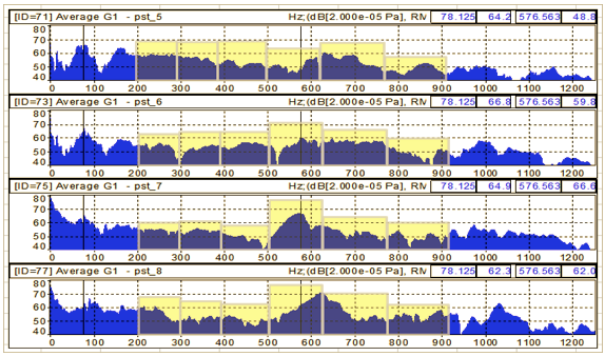

Figure 3. Prominence Ratio image and map of the tests

In a very simple and straightforward explanation, the Prominence Ratio PR is calculated by the following schematic formula (valid for pure tones of f > 174Hz):

$$\Lambda L_p = 10\,Log_{10}\left[\frac{X_M}{(X_L + X_U)*0.5}\right] \qquad (1)$$

In which XM, XL, XU represent the dB levels of the Sound Pressure in Critical Bands - Central (M), Lower (L) and Upper (U) respectively.
Considering to measure the Sound Pressure Levels and add on dB values, the applicable formula becomes:

$$\Lambda L_p = 10\,Log_{10}\left(10^{L_M/10}\right) - 10\,Log_{10}\left[\left(10^{L_L/10} + 10^{L_U/10}\right)*0.5\right] \qquad (2)$$

The PR consider whether a "noise" is concentrated in one or in another Critical band in respect of the two on each side (hum), while the TNR needs a "narrow" discrete frequency component, it is much more alike a tonal phenomena (whistle).
The following table n.1 (partial data set example) reports the correlation between the PR parameters values and the Visual Test decision by the Officer and Workers present at the experimental session.

The Visual Test gives a judgement which was classified as:
Deteriorated ➔ tile need to be changed
Time limited ➔ shall be changed soon, 2nd choice
Good ➔ tiles are in good state and do not need to be changed

Table 1: Correlation of PR data vs. visual inspection judgement (partial data set)

F_pr (Hz)	PRmean (dB)	ID tile	Visual test
1309.4	5.1	GR2-pst08	deteriorated
884.4	5.4	GR2-pst04	deteriorated
1350	5.6	GR2-pst13	deteriorated
496.9	5.7	GR2-pst10	deteriorated
453.1	6.6	GR2-pst06	broken
453.1	6.8	GR2-pst07	very good
593.8	6.9	GR1-pst9.	good
946.9	8.5	GR2-pst03	very good
496.9	8.5	GR2-pst12	time limited acceptance
496.9	8.7	GR2-pst02	time limited acceptance
1571.9	8.9	GR2-pst15	time limited acceptance
531.3	9	GR1-pst13	good
581.3	9.2	GR1.-pst1	good
543.8	10.1	GR1-pst11	good
543.8	10.1	GR1-pst14	good
581.3	10.9	GR1-pst8.	good
581.3	10.9	GR1-pst7.	good
571.9	11	GR2-pst14	good
531.3	13.7	GR2-t01->	very good
618.8	14.7	GR1-pst15	best

According to the above results, it becomes clear that there is a reasonable correlation encouraging to adopt an acoustic type survey methodology to determine the roof coverage tiles status. The discriminating index has been identified in the value of the PR index (Prominence Ratio) with a possible scale for which the single tile replacement could be decided.
The value of the PR Index expresed in dB values can be then assumed and defined as:

- PR <7 = need to change tiles for sure
- PR > 8.5 = tile status acceptable or good.

4 Final considerations

The assignment from the building owner was to discover and verify a Non Destructive Test (NDT) investigation method to identify which elements of the roof coverage show deterioration or other damage from ageing; in this way it becomes easy to consider and evaluate the tiles suitable or not to withstand a pedestrian load, even in the wosst case of people running in a dangerous situation.
The experimental data and the experiment itself show that the goal can be achieved considering an acoustic approach by artificially exciting the individual tiles with a rubber hammer and detecting the acoustic response in terms of Prominence Ratio expressed in dB values.
The full roof coverage of more than 10.000 tiles was laterfully investigated, confirming the methodology expectations; this allowed to change about 1/3 of the total number of tiles instead of redoing all the coverage work with a considerable time and economic saving.
Among the huge amount of over 10.000 tiles data we also introduced a subjective "jury testing" information given

by the operators performing the test; these additional results will be presented later.
In the present work we applied a Psychoacoustic metric to identify “different” sound emission and there is no connection with the traditional field of application covered by International standard.

References

[1] ANSI S1.13-2005 “Measurement of Sound Pressure Levels in Air”

[2] 1 ECMA-74 - 12th Edition / December 2012