

PRACTICAL ASPECTS FOR AUTOMATING THE ACOUSTIC RESONANCE INSPECTION OF CERAMIC ROOF TILES WITH COMPLEX GEOMETRY: TOWARDS REPLACING MANUAL INSPECTION

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ABSTRACT

In many ceramic roof-tile factories, quality control still relies on manual auscultation by operators, which causes fatigue, human variability and a non-negligible proportion of false positives and false negatives in the detection of internal cracks and fissures. This work assesses the ability of an automated impulse-excitation testing system (Grindosonic) to discriminate between conforming and non-conforming industrial tiles, both in a static configuration and on a production line, considering complex geometries with valleys, lugs and grooves. The influence of the engobe, of the mass, of the thickness and of the temperature of the parts is also discussed. Based on a plant test campaign with conforming tiles and tiles with light fissures and severe cracks, an intuitive learning and implementation protocol is proposed that combines the selection of suitable vibration modes, the tuning of the experimental strategy (support points, repeatable impact point) and the construction of robust OK/NOK decision criteria compatible with automation. The results show that the acoustic signature of the tiles makes it possible to reliably distinguish the integrity states, reducing the dependence on traditional human inspection and opening the way to a more repeatable and traceable non-destructive quality control for high-throughput lines.

KEYWORDS

Acoustic resonance, Ceramic roof tiles, Non-destructive testing (IET), Automated quality control

1. INTRODUCTION

Quality control of ceramic roof tiles in the factory still frequently depends on operators who carry out a manual acoustic evaluation in order to separate sound parts from parts with defects such as fissures, cracks or other internal flaws. This approach has well-known limitations: operator fatigue, ergonomic risk from repetitive movements, inter-individual variability and the unavoidable presence of false positives and false negatives when the decision relies on the human ear and on accumulated experience. In this context, an automated non-destructive inspection system based on acoustic resonance is especially attractive for high-throughput lines and for defects whose acoustic signature is not always perceptible to the inspection operators ("sounders") in the plant.

Automated systems based on this principle have been implemented in line and coupled with optical systems capable of detecting visual defects. However, the ability to avoid false positives and false negatives remains a point of vigilance in several tile plants that have invested in acoustic detection over the last 10 years. In fact, most plants continue to use human operators for lack of a practical solution. The quality of an instrument and its ability to perform a multimodal analysis, adapting to a high throughput and to ambient noise, are key factors in meeting the need for reliable quality control. However, the user's understanding of the acoustic signature of their tiles on the conveyor belts where inspection takes place, as well as of the possible causes of artefacts, are equally elements to be integrated. The present study proposes, on the basis of case studies, an intuitive learning and implementation protocol for in-line inspection by the user, employing a state-of-the-art instrument (Grindosonic MK7), in order to overcome the practical obstacles.

The impulse-excitation technique (IET) is based on applying a light impact to the tested body and analysing its natural resonance frequencies and, where appropriate, the associated damping. The ASTM E2534 standard (1) uses these phenomena to characterise rigid parts and to detect deviations linked to changes in stiffness, porosity, mass or structural integrity. The technique is also widely used to determine dynamic elastic moduli (E, G, Poisson: ASTM E-1876 (2): Fig. 1) and, particularly in the case of ceramic materials, to follow the evolution of fissures towards more open cracks. The effect of wear and physico-chemical attack, thermal shocks and other cyclic loads (3) can be analysed by this same technique in order to identify degradation thresholds, taking advantage of the fact that the resonant response of these materials is usually sharp and repeatable.

It is therefore possible to perform the same work as in-line sounder operators, by analysing the sound due to the resonant response produced by the impact of an automated hammer on the surface of the tiles, and to distinguish good parts from parts with moderate or severe defects (4), when the excitation and the vibration mode are suitably selected. The interpretation of the results must take into account that the resonant response depends simultaneously on the geometry, the mass and the activated modes, so that the experimental strategy (support point, impact position and pick-up point) is as important as the classification algorithm. It should be noted that parts excited by an impact can resonate according to various modes (bending, torsion, compression) along the 3 dimensions of the part (Fig. 2).

segun diversos modos (flexion, torsion, compresion) segun las 3 dimensiones de la pieza (Fig. 2).

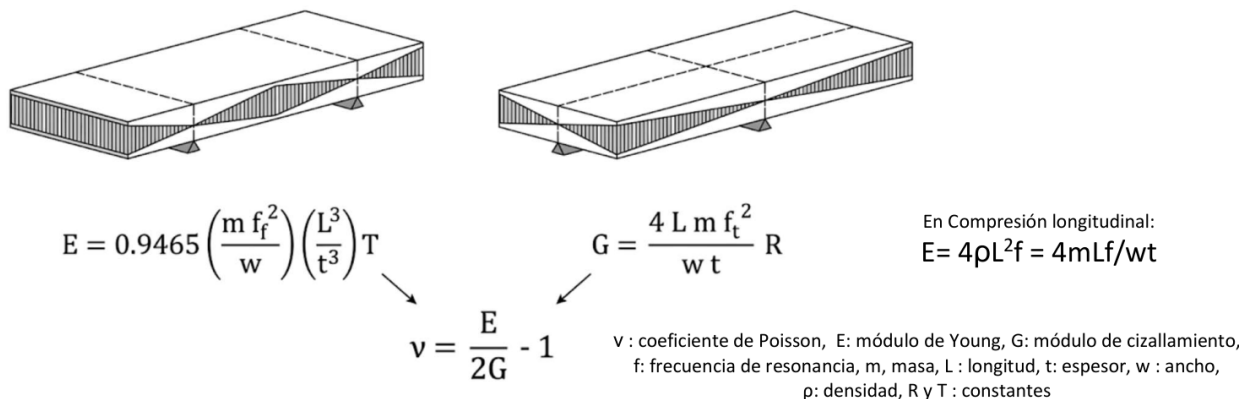


Fig. 1 medición de constantes elásticas dinámicas (E, G, Poisson) por método ASTM E1876

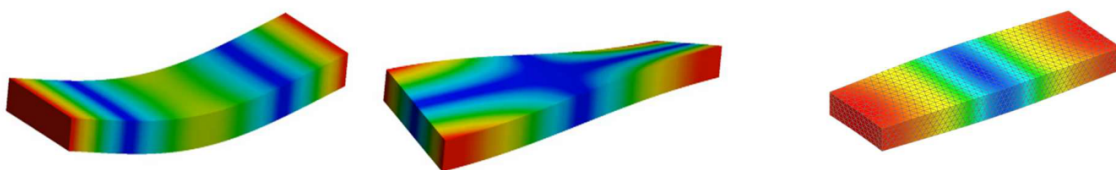


Fig. 1: measurement of dynamic elastic constants (E, G, Poisson) by the ASTM E1876 method

Note: the formula symbols within the image remain in the original Spanish.

Fig. 2: Modos de resonancia (a) en flexión longitudinal (generada mediante un impacto en el centro), (b) en torsión (impacto en una esquina) y (c) en compresión longitudinal (impacto en la punta)

Fig. 2: Resonance modes (a) in longitudinal bending (generated by an impact at the centre), (b) in torsion (impact at a corner) and (c) in longitudinal compression (impact at the tip)

In longitudinal compression: $E = 4\rho L^2 f = 4mLf/wt$

v: Poisson's ratio, E: Young's modulus, G: shear modulus, f: resonance frequency, m: mass, L: length, t: thickness, w: width, ρ : density, R and T: constants

A simple part (e.g. floor tile, brick, cylinder) can resonate according to a reduced number of distinct modes, with few typical fundamental frequencies and their harmonics. The stiffer the material, the higher its frequencies. Now, when the geometry of the part becomes richer (tiles with elbows, lugs and grooves, or 3D parts, sanitaryware, brake discs, etc.: Fig. 3), the acoustic signature of the parts will include new peaks and will become more complex. The ASTM E2534 standard states that damage to a part usually leads to the decrease of certain typical frequencies, to the disappearance or appearance of certain peaks, or to the broadening of those peaks in the frequency space. This broadening (peak width at half height) corresponds to damping ("attenuation") and increases from the onset of microcrack formation until it stabilises when these turn into more open fissures (6). For this reason, in the characterisation of industrial tiles, conforming ("OK") and non-conforming ("NOK") parts can usually be easily differentiated by the sole variations of their frequencies (Fig. 4).



Fig. 3: Front and back of the studied model (note valleys, lugs, grooves). "Crack" defect

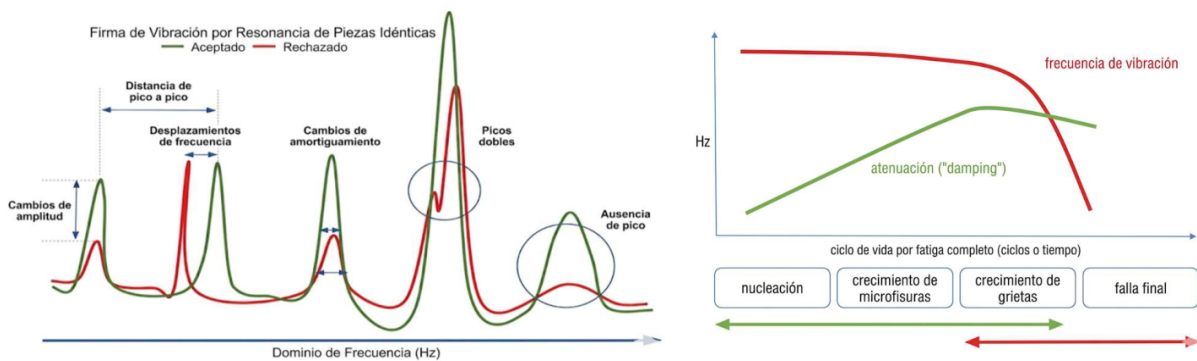


Fig. 4: (a) Detection modes of NOK parts according to the ASTM E2534-2020 standard (1) and (b) evolution of damping with the growth of fissures (6)

Note: the chart labels within the image remain in the original Spanish.

In the present work, the ability of the GrindoSonic MK7 system (Leuven, Belgium) to discriminate between OK and NOK industrial tiles is studied, both in a static configuration and in a dynamic configuration on the line, and its potential to replace traditional human inspection is discussed. The main focus corresponds to the detection of "fissures" or "cracks" (Fig. 3) and to the construction of robust OK/NOK decision criteria compatible with automation.

This study takes into account the effect of using or not using engobe and the configuration of the inspection line in the plant. It also evaluates the impact of additional factors such as variations in mass, thickness and temperature.

2. METHODOLOGICAL FRAMEWORK: LEARNING AND IMPLEMENTATION OF IN-LINE INSPECTION

A test campaign was carried out at a French tile plant, testing the same model with and without engobe, 46 cm in length, 30 cm in width, weighing 4.3–4.4 kg depending on the case. The frequency measurements covered tiles considered conforming and tiles with light defects ("fissures") or severe ones ("cracks"). The protocol applied to optimise in-line inspection includes the following phases:

(A) Learning to know the part "free": Tiles of the same model, OK and NOK, are placed on a foam-rubber support soft enough to allow freedom of movement in order to identify all of their resonance modes. By using different impact points and microphone positions, all the typical frequencies are identified and the frequencies that best distinguish OK and NOK parts are chosen, for quality control. This phase (A), like phase (B), takes 10 to 20 minutes (Fig. 5, 6).



Fig. 5: Tile learning protocol: (A) "free", (B) "captive on bars", (C) on the industrial line

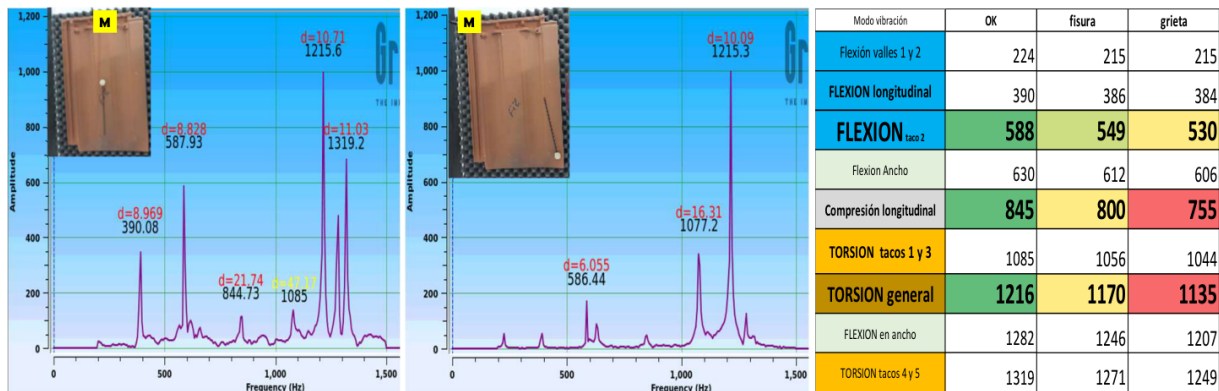


Fig. 6: "Free" learning: identification of the resonance modes: (a) bending (b) torsion according to the position of the hammer and the microphone ("M"), (c) identification of peaks that differentiate OK and NOK tiles.

Note: the table and chart labels within the image remain in the original Spanish.

(B) Learning to know the part "captive" on conveyor belts: the same tiles are placed on two parallel bars spaced (a) 14 cm and (b) 25 cm apart, as a simplified simulation of the conveyor belts of 2 different industrial production lines in the plant. Under these conditions, certain resonance modes (torsion, width-wise bending, longitudinal compression) may be less activated than the "longitudinal bending" mode when a hammer blow is applied to the centre of the tile. This "captive" mode is useful to confirm the frequencies of interest for quality control. In this study it also made it possible to identify the effect of a possible change in reading if the location of the impact point is not exact (2 cm from the centre of the tile, or more). Tolerance ranges are then set on the peaks of greatest interest. Parts whose values fall outside the range will be declared NOK (Fig. 7).

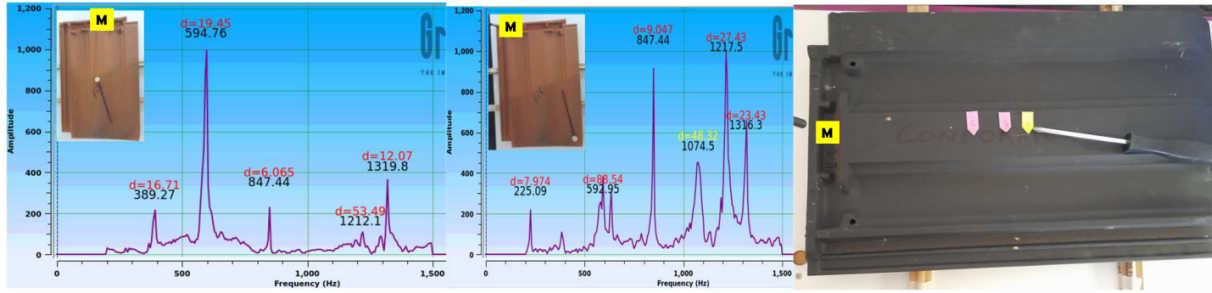


Fig. 7: "Captive" learning on parallel bars: (a) bending and (b) torsion. (c) Bending impact test, at 3 points (see arrows) on an engobed tile to visualise the effect of an impact far from the centre.

Note: the chart labels within the image remain in the original Spanish.

(C) Inspecting the parts in a real situation: the frequencies of interest are measured on industrial line "a" (14 cm), with an automatic hammer and real-time reading, in order to assess the compatibility between the readings of the instrument and the perception of the sounder operator (Fig. 8).



Fig. 8: Industrial line test with the hammer, FFT spectrum or QC software screening (Green/Red)

The parameters used for the measurements are given in Table 1. It should be noted that the purpose of the static learning in the laboratory (A) on foam rubber and (B) on parallel bars is to identify all the vibration modes associated with the tiles, which is why it is chosen to increase the sensitivity of the instrument (pre- and post-amplification), in order to better identify each typical frequency.

Sampling frequency	200 kHz
Number of points per measurement	32768
Resolution	6 Hz
Acquisition time per impact	0.163 s
Pre-amplification for measurement:	
- In the laboratory	× 6
- On the production line	× 2
Post-amplification for measurement:	
- In the laboratory	× 10
- On the production line	× 6
Other settings:	In the laboratory, ignore peaks with amplitude below 10% of the maximum peak, versus 20% in the plant

Table 1: measurement parameters of the Grindosonic MK7

In the plant, by contrast, it is necessary to reduce this sensitivity in order to disregard the parasitic sounds of the plant environment (nearby pneumatic devices, distant impacts unrelated to quality control), and to "listen" only to the impacts of the pneumatic hammer on the tiles in the automated inspection line, just as a sounder operator does. The acquisition time (0.163 s) is chosen so that the measurement and processing speed exceeds the industrial production rate (approx. 3000 parts/hour). The associated resolution (6 Hz) is considered sufficient to distinguish good and defective parts, whose frequency differences are greater than 20 Hz at the peaks selected for screening. A higher resolution (down to 0.02 Hz) is permitted by the instrument, but would have led to acquisition times of several seconds. On the other hand, it has been observed, on the industrial line, that the position of the hammer is a parameter to be monitored carefully: it is understood that an impact near the same point should generate the same spectrum. However, the complex shape of the tiles (lugs, grooves) could generate a different sound if the hammer is moved too far. In fact, sound artefacts have been observed in production, capable of confusing the sounder operator on shift, on a line fed by robots where it is suspected that the automatic hammer did not always strike the tiles at the same point. It is therefore necessary to identify how repeatable the signal is and with what margin. For this reason, the spectra are compared in "captive" mode (parts on parallel bars), striking OK and NOK tiles at their centre, as well as 2 cm and 6.5 cm away from it (Fig. 7).

3. RESULTS AND DISCUSSION

The test with tiles without engobe on a foam-rubber support ("free") makes it possible to reveal each of the various resonance modes (longitudinal bending, transverse, others) by placing the microphone-hammer pair in various directions (Fig. 6). Sound, fissured and cracked parts are clearly discriminated, especially at bending peaks around 588 Hz, longitudinal compression around 845 Hz and torsion around 1216 Hz. The geometric complexity is revealed when specific peaks are visualised upon impacting the lugs of the tiles. Fissures and cracks generate significant reductions of the typical frequencies (20–47 Hz and 33–92 Hz respectively). It is also observed that certain peaks are little affected by these defects (390 Hz). The same tile model is sometimes covered with an engobe rich in manganese oxide before firing, to give it a grey-black colour. Figure 9 shows spectra comparable to those of the tile without engobe (Fig. 6) although their frequencies for the OK parts are shifted by 3.5%. This shift could be linked to production variations in the mass m ($\pm 1.3\%$) or the thickness t (engobe: $\pm 0.04\%$) and/or in the level of sintering. To find out, the relative and absolute frequency variations at constant Young's modulus (E) or at constant shear modulus (G) are calculated, which are derived from the equations of Figure 1:

$$\text{In Bending: } \frac{\Delta f}{f} = \frac{1}{2} \times \left(3 \frac{\Delta t}{t} + \frac{\Delta m}{m} \right) = \pm 0.71\% \text{ that is, here } 588 \text{ Hz} \pm 4 \text{ Hz}$$

$$\text{In Compression: } \frac{\Delta f}{f} = \left(\frac{\Delta t}{t} + \frac{\Delta m}{m} \right) = \pm 1.34\% \text{ that is, here } 845 \text{ Hz} \pm 11 \text{ Hz}$$

$$\text{In Torsion: } \frac{\Delta f}{f} = \frac{1}{2} \times \left(\frac{\Delta t}{t} + \frac{\Delta m}{m} \right) = \pm 0.67\% \text{ that is, here } 1216 \text{ Hz} \pm 8 \text{ Hz}$$

Within this framework, variations in mass or dimension generate frequency variations that are close to the resolution chosen for the instrument, and are much smaller than the experimental shifts of the peaks. The large frequency differences measured between parts (engobed or not) are therefore essentially due to a different level of sintering and stiffening. A greater sintering of the product, associated with a reduction in porosity, leads to an increase in the Young's modulus and in the typical bending frequency (5). For this reason, the difference between OK and NOK parts of the same batch (3.8–6.6% for fissures and 6.7–10.7% for cracks) is solely attributable to the appearance of the defects. The 3 peaks considered are therefore retained as the main OK/NOK selection criteria. If the tile changes its Young's modulus from one batch to another (different firing), the whole set of OK/NOK frequencies will be shifted, but it can easily be identified with the learning

sequence described here. Moreover, it is observed that the longitudinal compression frequency drops significantly when fissures and cracks appear, but returns to the value of an OK part when the crack opens exceptionally (here: 65% of the length of the part).

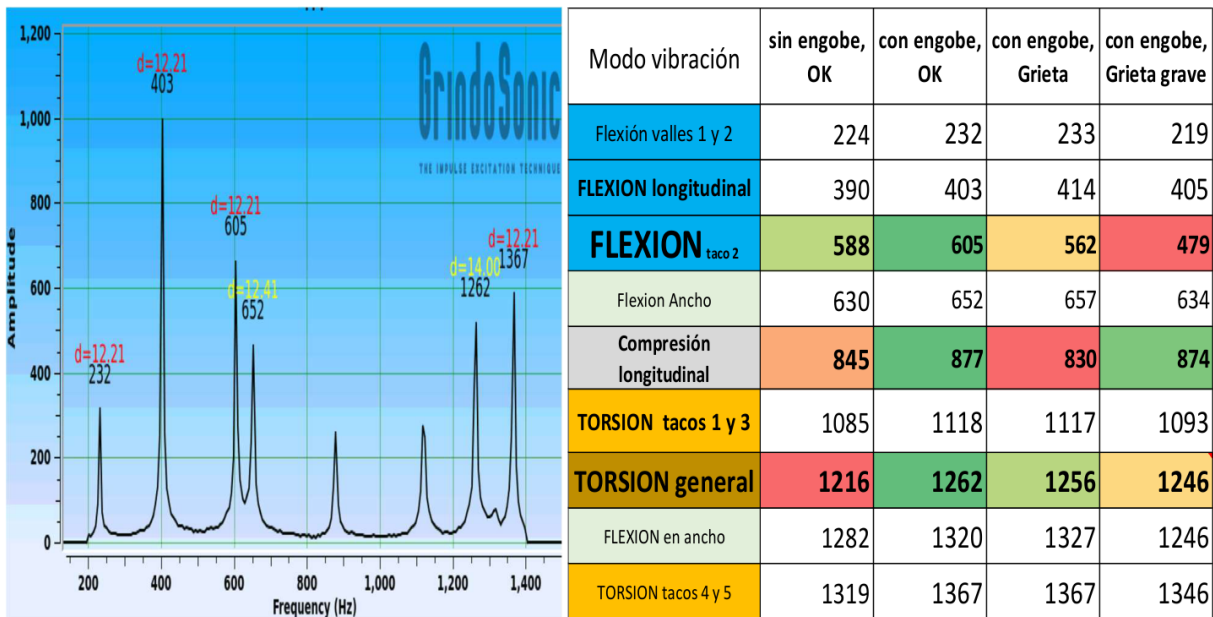


Fig. 9: "free" measurements on engobed tiles, compared with the same model without engobe

Note: the table and chart labels within the image remain in the original Spanish.

It should be noted that a study carried out for the same plant on another tile model (7), which was heated between 30 and 80 °C, yields a linear decrease of the typical resonance frequencies, with a variation of 0.08% (0.7–1.3 Hz) per 10 °C change in tile temperature. This factor is therefore likewise considered negligible compared with the behaviour of the material itself.

The second part of the test protocol ("captive" mode: support with parallel bars) made it possible to show that those bars, necessary for transporting the tiles on the inspection line, slightly alter the values of the bending peaks, increasing them by 10 Hz (Table 3). When the centre of the tile is impacted, the "longitudinal compression" mode practically ceases to be activated: at 877 Hz only a residual peak is observed (Fig. 10a). The "torsion" mode (1262 Hz) remains clearly audible and without alteration of value.

In both cases (distances 14 or 25 cm between parallel transport belts), the signal is preserved and fairly similar as long as the impact takes place at the centre of the tile or in a nearby area (± 2 cm). When the impact point is moved excessively away from the centre of the OK tile (here: 6.5 cm), a residual peak around 560 Hz is added to the reading of the main 615 Hz peak (Fig. 10b). A similar spectrum (Fig. 10c) appears when the tile is NOK (crack). This shows that the distance between parallel bars (and, therefore, the type of production line) does not affect the selection criterion, but that the repeatability of the impact point is key.

To this false-positive effect (520–560 Hz) generated by the "off-centre" impact (6.5 cm from the centre) is added the fact that the longitudinal compression peak (877 Hz) is strongly activated in OK tiles, when it was almost inaudible in the same OK tile struck exactly at its centre. In fact, it is noted that NOK tiles (with crack), whatever the distance between bars, also activate the "longitudinal compression" mode, although with a reduced value of its frequency (e.g. 830 Hz instead of 877 Hz: Fig. 10c). In conclusion, the bending peaks (615 Hz) and torsion peaks (1260 Hz) are chosen for in-line inspection.

Modo de vibración	Teja libre sobre soporte de goma		
	Flexión	Compresión	Torsión
Impacto en centro de teja sobre soporte de goma	605	877	1260
Impacto en teja sobre 2 barras paralelas	Teja sobre barras distantes de 14 cm		
	Flexión	Compresión	Torsión
A : centro de teja	615	-	1262
B: a 2 cm del centro	615	-	1263
C: a 6,5 cm del centro	616	879	1243
Impacto en teja sobre 2 barras paralelas	Teja sobre barras distantes de 25 cm		
	Flexión	Compresión	Torsión
A : centro de teja	616	-	1261
B: a 2 cm del centro	617	-	1261
C: a 6,5 cm del centro	616	880	-

Fig. 2: espectro de una teja engobada OK y efecto de la distancia entre barras simulando las bandas de transporte y del punto de impacto sobre los valores le

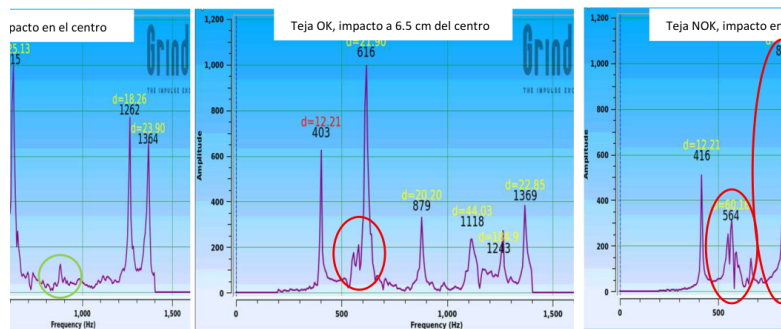


Fig. 3: espectro de una teja OK engobada, al impactar (a) en el centro (b) demasiado lejos del centro (c) teja engobada con grieta (impacto al centro): los picos 520-560 Hz generan falsos positivos

Table 2: spectrum of an OK engobed tile and effect of the distance between parallel bars (simulating the conveyor belts) and of the impact point on the readings

Note: the labels within the image remain in the original Spanish.

El test realizado en línea de producción industrial con barras distantes de 14 cm fue llevado a cabo sobre tejas con engobes, a una cadencia cercana a 3000 piezas/hora. Se observó que mientras el martillo impactaba la zona central de la teja, las evaluaciones OK/NOK del aparato y del operario sonador coincidían bien (tabla 3) y los chequeos de integridad realizados a posteriori por un sonador referente confirmaban las mediciones acertadas. Se confirmó que el sistema robot de descarga de las tejas – línea de transporte daba lugar, esporádicamente, a una disposición alterada de las tejas y, asimismo, del punto de impacto por el martillo automático de la línea: el golpe podía ocurrir lejos del centro de la pieza o incluso en el vacío. En estas condiciones, tanto el operario como el aparato daban lugar a una evaluación errónea (falso positivo). Frente a la confusión generada por el sonido alterado, el operario se veía obligado a dar varios golpes adicionales

Fig. 10: appearance of the spectrum of an OK engobed tile, impacting (a) at the centre (b) too far from the centre (c) engobed tile with crack (impact at the centre): the 520–560 Hz peaks generate false positives if the impact is made too far from the centre.

Note: the chart labels within the image remain in the original Spanish.

The test carried out on the industrial production line with bars 14 cm apart was performed on engobed tiles, at a rate close to 3000 parts/hour. It was observed that while the hammer struck the central zone of the tile, the OK/NOK evaluations of the instrument and of the sounder operator agreed well (Table 3) and the integrity checks carried out afterwards by a reference sounder confirmed the correct measurements. It was confirmed that the tile-unloading robot system – conveyor line gave rise, sporadically, to an altered placement of the tiles and, likewise, of the impact point of the line's automatic hammer: the blow could occur far from the centre of the part or even in the void. Under these conditions, both the operator and the instrument gave rise to an erroneous evaluation (false positive). Faced with the confusion generated by the altered sound, the operator

was forced to give several additional blows with a metal bar on the surface of the suspect tile before being able to issue a verdict: this results in losses of time and production, as well as in greater operator strain.

This synchronisation problem of the hammer-tile pair, which is intrinsic to the line studied and independent of the chosen detection mode (human or with the instrument), is being addressed by the company. Tests are planned on another production line, free of the mentioned spectral artefact.

OK/NOK	Limite bajo pico 1	Limite alto pico 1	FLEXION	Limite bajo pico 2	Limite alto pico 2	TORSION
	580	640	595	1247	1300	1249
	580	640	602	1247	1300	1262
NOK	580	640	562	1247	1300	1255
	580	640	604	1247	1300	1262
	580	640	623	1247	1300	1272
	580	640	624	1247	1300	1291
	580	640	628	1247	1300	1298
	580	640	609	1247	1300	1267
	580	640	598	1247	1300	1251
	580	640	599	1247	1300	1297
	580	640	609	1247	1300	1275
	580	640	628	1247	1300	1271
	580	640	616	1247	1300	1278
	580	640	603	1247	1300	1265
NOK	580	640	589	1247	1300	1238
	580	640	592	1247	1300	1240
	580	640	598	1247	1300	1256
	580	640	601	1247	1300	1250
	580	640	626	1247	1300	1256
	580	640	600	1247	1300	1262
	580	640	599	1247	1300	1249
	580	640	601	1247	1300	1260
	580	640	614	1247	1300	1271
	580	640	605	1247	1300	1259
	580	640	622	1247	1300	1273
	580	640	603	1247	1300	1252
	580	640	619	1247	1300	1254
NOK	580	640	585	1247	1300	1238
	580	640	585	1247	1300	1277
	580	640	603	1247	1300	1264
	580	640	593	1247	1300	1247
	580	640	591	1247	1300	1274
	580	640	590	1247	1300	1252
	580	640	602	1247	1300	1248
	580	640	592	1247	1300	1244
	580	640	602	1247	1300	1247
	580	640	596	1247	1300	1253

Table 3: extract of the OK/NOK part screening (engobed tiles) in the MK7 QC software mode on an industrial line with conveyor belts (14 cm), striking correctly at the centre of the tiles

Note: the labels within the image remain in the original Spanish.



Fig. 11: (a) Line configuration with unloading robot and (b) bars 14 cm apart; (c) configuration with bars 25 cm apart

4. CONCLUSIONS

The results obtained confirm that the GrindoSonic MK7 system offers great potential to replace the manual acoustic inspection of ceramic roof tiles on high-throughput lines, both in static tests and in dynamic configurations on conveyor belts. Its multimodal capability to excite and analyse bending, torsion and compression modes, together with electronics adjustable to noisy environments and high production rates

(more than 3000 parts/hour), makes it possible to reliably discriminate between OK and NOK parts, even in complex geometries and with variations in mass, engobe, sintering level or temperature within the usual industrial ranges. In the tests carried out, a good agreement between the decisions of the instrument and those of the sounder operator has been demonstrated, and in certain cases a better sensitivity to fissures and cracks that are difficult to perceive by ear, which translates into greater repeatability, better digital traceability of the inspection and an expected reduction in the arduousness and the risk of musculoskeletal disorders associated with repetitive manual striking. The proposed three-stage learning methodology (free part, part captive on parallel bars and finally on a real line) offers the industrial user an intuitive protocol to select the useful modes, set acceptance windows and adapt the system to different tile models and production conditions. Nevertheless, the tests have highlighted the critical importance of ensuring the repeatability of the hammer impact point on the tiles travelling on the conveyor belts, since excessive displacements with respect to the centre of the tile can activate additional resonance modes and generate spectral artefacts (in the case of bending) that translate into false positives, capable of confusing both the automated system and the operator. This aspect, linked to the hammer-tile synchronisation and to the positioning provided by an unloading robot, must be considered an essential point of vigilance in any project to automate acoustic resonance inspection. Overall, the study confirms the viability of the system as a robust non-destructive inspection tool for industrial manufacturers of ceramic roof tiles, provided that the user integrates, in the implementation phase, a prior reference-characterisation work and a rigorous control of the mechanical excitation conditions in line. As a natural continuation of this work, it is planned to extend the campaigns to other production lines and to other tile models, as well as to optimise the screening algorithms and the integration strategies with optical and process-supervision systems, with the aim of consolidating a complete industrial solution that is easily transferable to different factories.

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6. NOTE

An artificial-intelligence tool was used exclusively for grammatical and stylistic correction; all interpretations and conclusions are the responsibility of the authors.