Technical Condition Assessment of Masonry Structural Components using Frequency Response Function (FRF)

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ABSTRACT
The international standards indicate the need for an adequate quality control in the production of masonry in bricks (light bricks, double bricks, insulating bricks, breeze blocks, concrete blocks, etc.). This quality control focuses on a set of criteria for establishing the technical condition of the bricks. The quality estimation methods, the technical condition assessment and the formulation of safety parameters for bricks are studied in this work. The paper proposes a non-intrusive method to test bricks in production plant conditions, focused on quality control process, as a method of conformity belonging to a production line to identify the structural condition of the bricks, based on Frequency Response Function (FRF).

KEYWORDS: accelerance function, frequency response function, masonry component, non-intrusive test.

NOTATIONS

$A_{\omega\alpha}$	belonging area into FRF
c	damping coefficient
$f(t)$	force in time domain
$F(\omega)$	input force in frequency domain
j	complex component
k	stiffness coefficient
m	mass
S_F	fault condition of brick
S_R	reference condition of brick
p	point of FRF function
P_{ctl}	control points of FRF function
P_{Fi}	*i-th* fault point of FRF function
P_{Ri}	*i-th* reference point of FRF function
$X(\omega)$	output displacement in frequency domain
$\ddot{X}(\omega)$	output acceleration in frequency domain
w_F	hypotheses of brick with fault condition
w_R	hypotheses of brick without fault condition
$\alpha(\omega)$	FRF function in frequency domain
$\alpha^i_{A(test)}$	tested FRF function in *i-th* direction

1. INTRODUCTION

The detection of structural damage is an issue that has been given priority in industry (aviation and aerospace field, particularly) [1]. Recently, the detection of the structural damage has been applied to civil structures (bridges, buildings, foundations and roofs) [2]. The technical condition assessment of bricks has an influence on the safety and lifetime of structures, and hence the detection of structural damage is important in the planning of structures.

Experimental Modal Analysis (EMA) was adopted from dynamics, in mechanical engineering [3–5]. EMA is applied universally to dynamic properties research of various structures [6]. EMA has been used to assessment of civil structures, steel members (such as oil platforms, bridges, etc.) [7] or castings (such as centre spindles in wind turbines) [8], to determine conditions of installation and degradation. For damage detection, EMA is supported in the fact that the dynamic response of a structure is modified with damage; this allows the possibility of identifying damage in structural variations of response before and after the damage occurs [2, 4]. Particularly, damage detection formulates a relationship between damage and changes in the modal parameter of a structure [7].

The state of art exposes studies of concrete strength by combined non-destructive methods via impact hammer and ultrasonic pulse velocity tests, in order to arrive at a chart for strength evaluation [9]. Other studies are focused on prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks [10]; the ultrasonic pulse velocity values are affected by a number of factors, which do not necessarily influence the concrete compressive strength in the same way or to the same extent. Others previous studies analyse a technique for the quality identification of building masonry elements based on EMA [11], which the modal properties have been identified by using multiple methods: (*i*) least-square complex exponential method to calculate the stabilization diagram, and (*ii*) coherence function. All the identified studies in the state of the art are limited, due to the tests require considerable resources in terms of the data processing, as well as the tests require laboratory conditions to be applied and the implementation of the algorithms; then, the execution of those tests becomes complex and expensive.

This paper proposes a new method to assess the damage level of building structural components (bricks, slabs, concrete blocks, etc.) into a factory line production via non-intrusive test, in production plant conditions; i.e. the test requirements are adjusted to factories conditions, besides the data processing and computing have low requirements, then it is possible to carry out the test in a real-time analysis at a line-production. The work is based on the Frequency Response Function (FRF) which is able to estimate the technical condition of bricks.

FRF represents the relation between the input and output of data set signals [3]. The bricks can be idealized as elements with a Single Degree of Freedom (SDoF), it provides an overall physical insight into the vibration of the bricks. The SDoF system is a mathematical model which uses the mass m, the stiffness k, and the damper c, with the structural (hysteretic) damping to each kind of brick. The structural damping is an alternative damping model of vibration analysis; this damping is originated from the hysteresis property of stress–strain curves [5].

For a harmonic input force $f(t) = F(\omega)e^{j\omega t}$, the response of the system is another harmonic function $x(t) = X(\omega)e^{j\omega t}$ where $X(\omega)$ has a complex amplitude. Substituting them into the equations of motion for a damping model [7], it is possible derive the ratio of the displacement response and the force input as

$$\frac{X(\omega)}{F(\omega)} = \frac{1}{k - \omega^2 m + jc}, \tag{1}$$

this ratio, often denoted as $\alpha(\omega)$, is defined as the FRF of the system. FRF uses displacement, $X(\omega)$, as the response;

it is known as reacceptance [3]. The vibration response also be given in terms of velocity, $\dot{X}(\omega)$, or acceleration, $\ddot{X}(\omega)$. In the case the vibration response is $\ddot{X}(\omega)$ a type of FRF called accelerance is defined for hysteretic damping [5]

$$\alpha_A(\omega) = \frac{\ddot{X}(\omega)}{F(\omega)} = -\frac{\omega^2}{k-\omega^2\,m+j\,c}. \quad (2)$$

2. DESCRIPTION OF THE PROPOSED METHOD

In experimental field, the $X(\omega)$ measurements are shown at low frequency range, and $\ddot{X}(\omega)$ measurements at high frequency range. It is known that $\dot{X}(\omega)$ measurements are suitable to researches for dynamics of civil structures with regard on the effective value, obtained by measuring the kinetic energy of modal shapes. However, sensors that measure $X(\omega)$ and $\dot{X}(\omega)$ have a considerable mass in relation to bricks mass, and it can influence the dynamic behaviour. The accelerometers have considerably lower mass, and therefore do not influence the behaviour of the arrangement. The accelerometers have an additional advantage, the fact that their signal can be integrated once or twice, $\int \ddot{X}(\omega)\,d\omega$ and $\iint \ddot{X}(\omega)\,d\omega$, to get $\dot{X}$ and X signals, respectively [11, 12].

The backwards mathematical operation depends on differentiating vibration, which can lead to error, in the higher frequency range, particularly; therefore, the sensors have their self-resonance, which limits the frequency in which they can be applied [11].

The experimental analysis process of modal bricks can be divided in four basic phases [3]: (*i*) measurements setting; (*ii*) test arrangement; (*iii*) data acquisition; and (*iv*) signals data processing.

2.2. Measurements setting

The test methodology was been develop and exposed in previous research [11], the object of study have been grouped regarding types of bricks masonry, which have been classified in two kinds of bricks: (*i*) hollow bricks; and (*ii*) solid bricks. This bricks were selected because they are the simplest elements of masonry, and many civil istructures are made in this technology. A set of 30 bricks (see Figure 1), provided a recognized brick tested producer in Bydgoszcz (Poland).

The proposed procedure is built in two stages: a first stage, in which the test results are obtained from a set of bricks without fault (as a reference); and a second stage, where a test results are obtained from a set of bricks with nonconformity production to identify and quantify the variation parameters. Then, half of the set of tested bricks had good condition to establish the reference of dataset, called S_R, in order to get the basis to compare with the other half of the set of bricks that had fault condition, called S_F. Each brick was checked during production using the standard quality control to bricks manufacturing [11], the bricks with S_R condition has been selecting; and then, to get the bricks with S_F condition, damage has been artificially produced in laboratory by making cracks on bricks.

A set of 90 tests has been developed under line-production conditions, each brick was tested at the principal directions: (*i*) x, longitudinal; (*ii*) y, lateral; and (*iii*) z, vertical.

2.1. Test arrangement

The accelerometers should be fixed in such way that they will not influence the arrangements performance [12]; as well as they should be fixed in characteristic points of the bricks.

The bricks must be fixed to a correct assemblage according to the input perturbations. Perturbations must be performed on object in normal operation; during experimental test, the mounting must have the correct boundary conditions to get realistic DoF. Then, the experimental test has been performed on a freely suspended condition to each brick (see Figure 2).

2.3. Data acquisition

The bricks (S_R and S_F samples) has been exited by an impact hammer with a built-in force transducer. The hammer was used to ensure proper excitation in frequency range of interest which from 0 to 6kHz.

The excitation-response performance has been recorded in a DAQ system by means of a set of single-axial piezoelectric accelerometers, PCB-352C68-ICP model. The signals in the time domain from DAQ system were exported to a real-time signal software package.

An input signal –excitation– $F(\omega)$ and an output signal –response– $\ddot{X}(\omega)$ are used for calculating the FRF.

The basic operation that can be done by the signals analyser is the analogue-digital processing, which makes possible to apply digital technology in processing the modal analysis signals [13].

2.4. Signals data processing

The experimental results are shown below in Figure 3, separately for all axes, FRF is applied to the input excitation data and the response to each brick condition. All datasets recorded are available from the authors of this paper. Figure 3 represents a characteristic pattern of the FRF behaviour, $\alpha_A\,(\omega)$, for the technical condition assessment S_R and S_F.

From this pattern a set of twelve control points, P_{ctl}, is selected. P_{ctl} is composed of two set of points of $\alpha_A\,(\omega)$ functions, one set from S_R and the another from S_F, then $P_{ctl} = \{P_R, P_F\}$, with $\left(P_R \in \alpha_{\mathrm{A}}(\omega) \vee P_F \in \alpha_{\mathrm{A}}(\omega)\right) \wedge P_R \neq P_F$, where $P_R = \{p_{R1}, \dots, p_{R6}\}$ and $P_F = \{p_{F1}, \dots, p_{F6}\}$.

Finally, after the tests, the sample of all bricks was checked using a traditional destructive method –load test– to validate the real technical condition of the set of tested bricks.

3. ANALYSIS OF THE RESULTS

A representative sample of bricks batch production must be defined. Each brick of the sample is subjected to a test, obtaining a set of FRF functions, $\alpha^i_{\mathrm{A}(test)}$ with $i = x,\ y,\ z$ corresponding to the principal directions.

The behaviour of each function $\alpha^i_{\mathrm{A}(test)}$ is compared to the corresponding characteristic pattern of the FRF behaviour, by means of identifying the control points P_{ctl}; therefore, the following stages can be proposed:

(*i*) identification of the control $\{p_{R1}, p_{R2}, p_{F1}, p_{F2}\}$ in the function $\alpha^x_{\mathrm{A}(test)}$;

(*ii*) identification of $\{p_{R3}, p_{R4}, p_{F3}, p_{F4}\}$ in the function $\alpha^y_{\mathrm{A}(test)}$; and

(*iii*) identification of $\{p_{R5}, p_{R6}, p_{F5}, p_{F6}\}$ in $\alpha^z_{\mathrm{A}(test)}$.

As a consequence, a method for identifying the relevance of a certain control point, $p \in P_{ctl}$, in a function $\alpha^i_{\mathrm{A}(test)}$, is developed. The method consists of:

(*i*) defining a belonging area $A_{\omega\alpha} = (2\Delta\omega) \times (2\Delta\alpha)$, centered at the control point p_{ctl} (see Figure 4); and

(*ii*) finding a maximum/minimum local value, $\alpha_{\mathrm{A}(MAX)}$, enrolled within the belonging area $A_{\omega\alpha}$, i.e. , $\exists \alpha_{\mathrm{A}(MAX)} \in A_{\omega\alpha}: p \equiv \alpha_{\mathrm{A}(MAX)}$; or

(*iii*) in the contrary case, i.e., that the maximum/minimum local value $\alpha_{\mathrm{A}(MAX)}$, is included in the belonging area

$A_{\omega\alpha}$, the relationship $\exists!\, \alpha_{\mathrm{A}(MAX)} \in A_{\omega\alpha}: p \equiv \Phi$ is obtained.

Two hypotheses in which the symptom will be classified are considered: w_R –without fault condition–, and w_F –failure condition–. The a-posteriori probability of each type is $P(w_i|S)$.The technical condition of the brick is w_R with a certainty convergent probability of $P(w_R|S) \cong 1$, in the case that every control point P_R belongs to the respective function $\alpha^i_{\mathrm{A}(test)}$, and besides, every control point P_F is excluded from the function $\alpha^i_{\mathrm{A}(test)}$, i.e.

$$\forall\left(P_R \in \alpha^i_{\mathrm{A}(test)} \wedge P_F \notin \alpha^i_{\mathrm{A}(test)}\right) : P(w_R|S) \cong 1, \qquad (3)$$

on the other side, the technical condition of the brick is w_F with a convergent certainty convergent probability of $P(w_F|S) \cong 1$, in the case that every control point P_R is excluded from $\alpha^i_{\mathrm{A}(test)}$, and besides, every control point P_F belongs to $\alpha^i_{\mathrm{A}(test)}$, i.e.

$$\forall\left(P_R \notin \alpha^i_{\mathrm{A}(test)} \wedge P_F \in \alpha^i_{\mathrm{A}(test)}\right) : P(w_F|S) \cong 1. \qquad (4)$$

In case that $\alpha^i_{\mathrm{A}(test)}$ has control points belonging from both technical condition, w_R and w_F, it means the brick is not good perfectly, but it has not a failure, as the ratio of the quantity of the control points P_F included from $\alpha^i_{\mathrm{A}(test)}$, and the total of the control points P_F and P_R included from $\alpha^i_{\mathrm{A}(test)}$, i.e.

$$\exists\left(P_R \in \alpha^i_{\mathrm{A}(test)} \wedge P_F \in \alpha^i_{\mathrm{A}(test)}\right) : P(w_R) = \frac{\sum\left(P_F \in \alpha^i_{\mathrm{A}(test)}\right)}{\sum\left(P_F \in \alpha^i_{\mathrm{A}(test)}\right) + \sum\left(P_R \in \alpha^i_{\mathrm{A}(test)}\right)} \qquad (5)$$

Then, with the equation it is possible to calculate the a-priori probability value, $P(w_R)$, in which the brick subjected to the test is in good technical condition.

4. CONCLUSIONS AND FUTURE WORK

The proposed method gives the possibility of automating the ongoing process to identify the technical condition of bricks, and for assessing the safety of civil structures as walls, buildings, high poles, chimneys, foundations for machinery and roofs.

There is a clear feasibility to implement the proposed method for bricks factories, due to: (*i*) the sensors and data acquisition systems are widely studied for technical elements that do not represent a challenge to the current industrial sector; (*ii*) the costs of implementation are low in relation to the amount of information that the process may obtain from the system.

The results show that the difference between good/fault technical condition of bricks can be estimated from the quality of $\alpha_{\mathrm{A}}(\omega)$ functions generated through processing from input to output signals.

The change on the building materials condition can be reflected in the change of the value and the character of course of the $\alpha_{\mathrm{A}}(\omega)$ function. Therefore, the possibility of distinguishing the property of the building material exists by using FRF.

The technical condition assessment using FRF is possible and convenient in building industry, due to FRF is a non-intrusive test. This characteristic allows 20% lower costs than traditional techniques by optimizing time, equipment and staff.

$\alpha_{\mathrm{A}}(\omega)$ functions are a suitable mathematical tool to evaluate bricks (light bricks, double bricks, insulating bricks, breeze blocks, concrete blocks, etc.).

The proposed methodology is useful whereas the data logging allows getting information in terms of commercial operation, avoiding measurements that require downtime for the system inspection.

The equation 5 represents an index to identify the technical state of the bricks and to define the quality control process in a line production of bricks factory. $P(w_R)$ value can be directly normalized to get an index into the scale defined by a national structural code.

The paper opens to different research fields, the elements can be considered for future studies, e.g. to establish the estimator value $P(w_R)$ limit to a particular brick and particular international standard.

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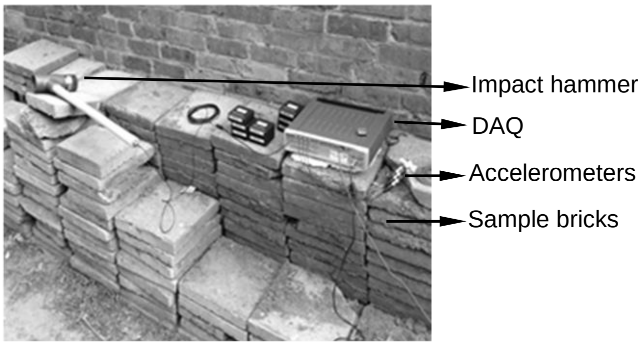

Figure 1 Experimental FRF test.

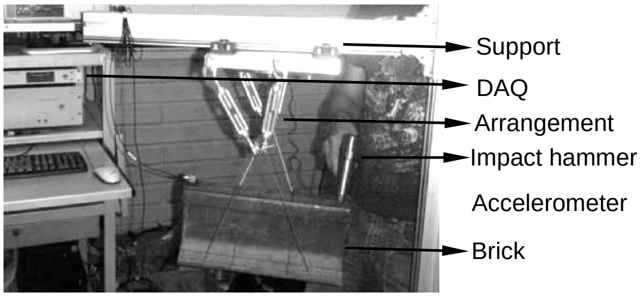

Figure 2 Test arrangement

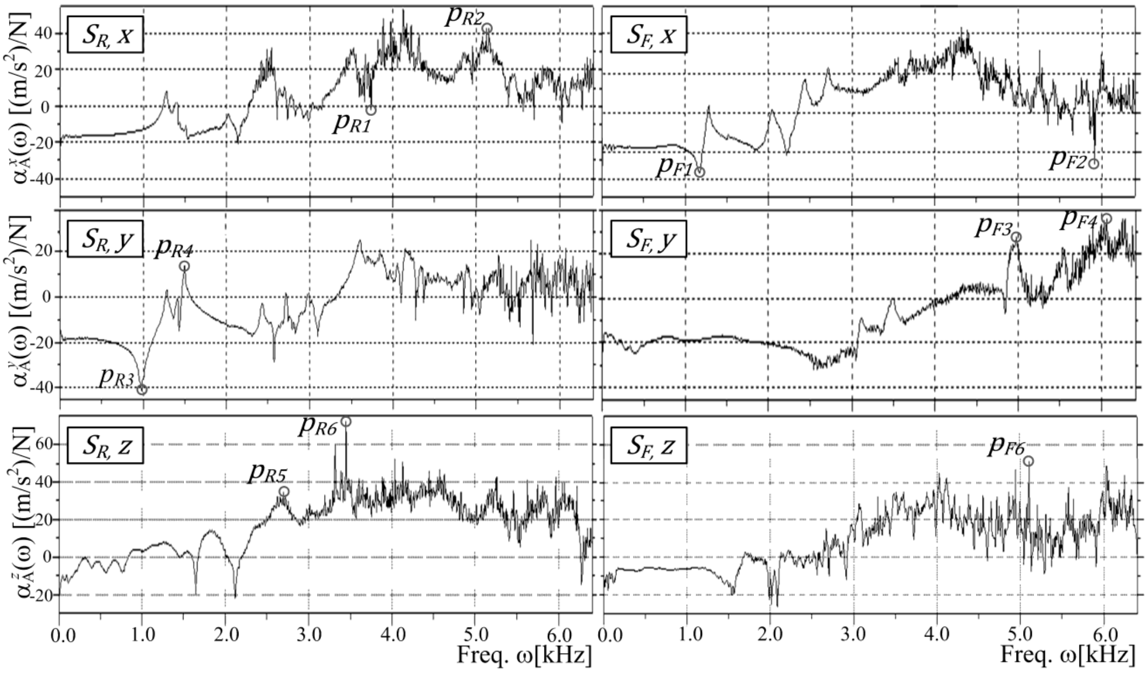

Figure 3 Characteristic pattern of $\alpha_A(\omega)$ at bricks different technical conditions.

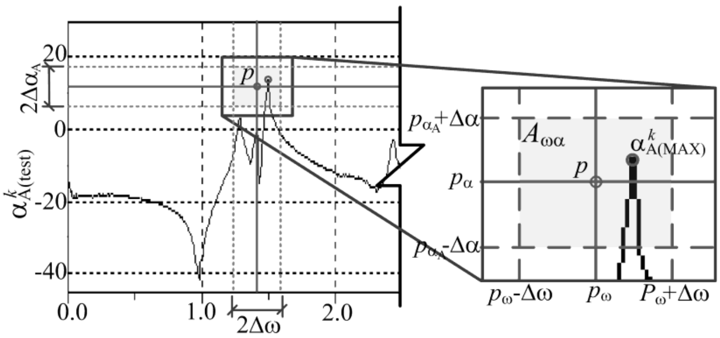

Figure 4 Identification scheme of the belonging p in $\alpha^i_{A(test)}$.