Quality identification methodology applied to wall-elements based on modal analysis

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Abstract

Purpose – The recommendation of structural standards, e.g. PN-B-03002, shows a need to control the production quality of wall-elements; the quality control demands suitable guidelines to fit the requirements of the current mass-production of the wall-elements, then, the structural standard recognizes the need of improving the methods to identify the real elements quality. The paper aims to discuss these issues.

Design/methodology/approach – The proposed inspection methodology corresponds to assessment models that combine the numerical and symptomatic models to evaluate the critical levels of wall-elements, based on non-intrusive tests through the measurement of a set of signals, using the Experimental Modal Analysis (EMA)-based techniques.

Findings – The presented work is developed with an approach that applies advanced calculating techniques used for the structural analysis in civil engineering focused on the technical state assessment.

Originality/value – The paper proposes a diagnostic methodology that can be added to the current regulations and standards based on EMA techniques.

Keywords Coherence function, Experimental modal analysis, Manufacturing quality, Stabilization diagram, Wall-element

Paper type Research paper

1. Introduction

Existing civil constructions and masonry structures, such as: buildings; chimneys; high poles; roofs; and machines foundation; are subject to dynamic effects caused by: the environment – wind, earthquakes and sea waves – and vibration or trembling events – explosions, machinery, railways and roadway vehicles. Vibrations in buildings can decrease living comfort, and has an influence on: the people working there; and threatening the safety level of the construction – the vibration events cause dynamic load and can generate catastrophic destruction (Giergiel, 2000).

The need of building civil constructions with dynamic fail-safe effects has been identified. To identify the quality of the wall-elements (basic bricks, breeze blocks, light bricks, repressed bricks, double bricks, insulating bricks, feather-edged bricks, etc.) there is a technical effort to project constructions and to improve the safety and stability of the civil constructions (Kaczmarek, 1993). The structural engineering

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then recognizes the need of improving the methods to determine the real quality of wall-elements used in constructions, by means of the assessment of wall safety coefficients defined by the structural standard (e.g. PN-B-03002). This standard requires establishing the partial coefficients of wall-elements, called safety coefficients, to classify the category of the works that are performed on buildings. Currently in a line production, the wall-elements quality control is made manually based on visual inspection; this method is subjective and do not evaluate the technical state of the element, i.e. the currently used method to identify the quality of wall-elements in line-production manufacturing is by: visual inspection (a technician watches the wall-element to find superficial cracks, or inconsistencies); measurement of mass; measurement of general dimensions (length, width, height).

In this paper, a technique for the assessment of the damage level of wall-elements has been adopted, based on non-intrusive tests through the measurement of a set of signals, using Experimental Modal Analysis (EMA)-based techniques. EMA is applied directly to wall-elements tests based on measuring the dynamic system excitation and response according to the classical modal analysis theory (Hanson *et al.*, 2007). EMA has been widely documented (Ewins, 2000; He and Fu, 2001; Genta, 2009), and the modal properties of dynamic systems can be identified using standard identification methods in time domain (Uhl and Kurowski, 2002; Uhl, 2006); then, the following methodology is proposed:

(1) to apply an excitation to the wall-element with an impact hammer, shaker, etc., and the excitation/response signals are recorded by means of a data acquisition system;

(2) to process the signals recorded though EMA-based techniques; the modal properties are identified by using two different methods:
   - least-square complex exponential (LSCE) method to calculate the stabilization diagram (SD) (Giergiel and Uhl, 1990); and
   - coherence function (Coh_{ij}).

(3) to determine an estimator that synthesize the SD and (Coh_{ij}) information, and in this way, the estimator identifies the technical state of the wall-element; and

(4) to normalize the estimator value to get an index into the scale defined by structural standards, e.g. the safety coefficients defined by PN-B-03002.

The theoretical basis of using modal analysis for damage detection lies in the fact that dynamic responses of a structure vary damage. This allows the possibility of identifying damage from variation in structural responses before and after damage occurs. In particular, damage detection formulates relationships between damage and changes in the modal parameter of a structure (Cempel, 2001; Tylicki, 1999).

The proposed inspection methodology corresponds to assessment models that combine the numerical and symptomatic models to evaluate the critical levels; these have been previously used by the authors in technical systems of railways and structure field (Żółtowski and Orłowicz, 2005; Żółtowski, 2005; Martinod *et al.*, 2012). The developed inspection methodology is feasible to be applied to the wall-elements mass-production, since it uses sensors (force sensor, accelerometers) of easy installation and operation, while they record reliable signals. The proposed approach can be used for better understanding the behaviour of constructions, which allows optimizing the projection and assessment of critical states.

2. Background

EMA is used to determine the behaviour of the wall-elements under given dynamic effects condition (Żółtowski, 2005; Martinod *et al.*, 2012). Consider a squared matrix $[A]$ of real numbers having a size of $n \times n$, eigenvalues λ_r, and corresponding eigenvectors $\{\phi\}_r$ with ($r = 1, 2, \ldots, n$); the $\{\phi\}_r$ family consists of independent vectors. The matrix of λ_r can be expressed in the form $[\Lambda] = diag\ [\lambda_1, \lambda_2, \ldots, \lambda_n]$, and the matrix of $\{\phi\}_r$ as $[\Psi] = diag\ [\{\phi\}_1, \{\phi\}_2, \ldots, \{\phi\}_n]$. The decomposition of eigenvectors produces the equation $[A] = [\Psi]\,[\Lambda]\,[\Psi]^{-1}$ (He and Fu, 2001).

The equation shows that $[A]$ may be expressed as a diagonal matrix in the form $[\Lambda] = [\Psi]^{-1}\ [A]\ [\Psi]$. For all range $[A]$, the only solution satisfying that λ_r and its corresponding non-null $\{\phi\}_r$ exist is when $([A]-\lambda_r[I])\ \{\phi\}_r = \{0\}$. This determinant can be expanded, obtaining a polynomial n for λ. The polynomial's roots are λ_r of $[A]$. If $\lambda_i = \lambda_r$, it means that there are identical modal shapes, a phenomenon that occurs frequently in symmetrical structures, in this case, symmetrical dynamic properties of wall-elements.

2.1 EMA-LSCE method

Using the properties upon which the natural excitation technique is based, the response functions can be used to determine the Impulse Response Function (IRF). The modal parameters of the system can be identified using standard identification methods in the time domain (Martinod *et al.*, 2013); in this paper, the LSCE method is used. Then, EMA associated to LSCE method assesses the global modal parameters: natural frequency Ω ($\sqrt{\lambda_r}$ is equivalent to Ω) and damping ratio ξ.

The IRF can be derived from the inverse Fourier Transform for a Frequency Response Function through the Power Spectral Density (PSD), the Random Decrement process, the inverse Laplace transform or other methods (Uhl and Lisowski, 1996).

The inverse Laplace transform of the transfer function of an MDoF system is the IRF, h_k. This gives as a result a series of equally spaced time intervals $k\Delta$ ($k = 0, 1, \ldots, 2n$), and then it is possible to express IRF as (He and Fu, 2001):

$$h_k = \sum_{r=1}^{2n} {}_rA_{ij} z_r^k; \quad \text{with } z_r^k = e^{s_r k\Delta}, \tag{1}$$

where:

$${}_rA_{ij} = \phi_{ir}\phi_{jr}. \tag{2}$$

This expression is the product of the ith and jth elements in the rth modal shape, $\{\phi\}_r$, and named as modal constant. The values in the series belong to the real numbers even if the residues and the roots s_r are complex values. It is possible to demonstrate that all imaginary parts will cancel each other because of the complex conjugates for both expressions: ${}_rA_{ij}$ and s_r. The next step is to estimate the roots and the residues for the sampled data. This solution is aided by the conjugate of the roots s_r, therefore, z_r. Mathematically, this means that z_r are the roots of a polynomial with only real coefficients (He and Fu, 2001):

$$\beta_0 + \beta_1 z_r + \beta_2 z_r^2 + \ldots + \beta_{2n} z_r^{n2} = 0 \tag{3}$$

or:

$$\sum_{k=0}^{2n} \beta_k h_k = \sum_{r=1}^{2n} {}_rA_{ij} \sum_{k=0}^{2n} \beta_k z_r^k. \tag{4}$$

This equation is known as the Prony equation. The coefficients can be estimated by the IRF values. An auto-regressive (AR) model is constructed by the relation between poles and residues, which are processed to perform the estimation of the poles given, as they provide information about the quality of the data and the computational resources requirements (a model of higher order imply a greater processing cost) (Uhl, 1997). The AR model solution allows to define a polynomial in whose roots the complex roots of the system are present; having established the roots (equivalent to the natural frequencies Ω and the damping rates ξ), the residues can be derived through the AR model and then the modal shapes $\{\phi\}_r$ can be obtained (He and Fu, 2001).

2.2 EMA-Coh_{xy} function

Coh_{ij} function finds the estimation of the magnitude squared coherence of an excitation signal, $i(f)$, and response signal, $j(f)$, in the frequency domain, using Welch's averaged, modified periodogram method. The magnitude squared coherence is a function of frequency domain with values a range of values [0, 1] that indicates how well $i(f)$ corresponds to $j(f)$. The coherence is a function of the PSD P_{ii}, P_{jj} of $i(f)$ and $j(f)$ and the cross-PSD P_{ij}, then: $Coh_{ij}(f) = |P_{ij}(f)| / (P_{ii}(f) \cdot P_{jj}(f))$.

$Coh_{ij}(f)$ is calculated whit a periodic Hamming window of length to obtain eight equal sections of $i(f)$ and $j(f)$, and the value to obtain and 50 per cent overlap.

3. Development of experimental test

The experimental test is the basic source of information to identify the technical state of wall-elements, and on its basis the values of measures in the structure of the modal model can be established. The identification experiment in EMA depends on the arrangement of perturbation sources (excitation input) simultaneous to the behaviour element (response signal). The EMA requires controlled conditions for the execution of investigations.

In modal investigations it is not relevant which of kinematic level of movement are being measured. In practice however the measurements of X are shown in a low frequencies range, and $\ddot{X}$ in a high frequencies range. It is known that the measurements of $\dot{X}$ are suitable to investigations for dynamics of construction with regard on the effective value, obtained by measuring the kinetic energy of modal shapes. However sensors that measure X and $\dot{X}$ have a considerable mass in relation to the wall-elements m, and they can influence their behaviour. The accelerometers have considerably lower mass, and therefore do not influence the movement of the arrangement. The accelerometers have an additional advantage, the fact that their signal can be integrated once or twice, $\int \ddot{X}(t)dt$ and $\iint \ddot{X}(t)dt$, to get $\dot{X}$ and X signals, respectively (Chauhan *et al.*, 2009). The backwards mathematical operation depends on differentiating vibration, which can lead to large mistakes particularly in the higher frequencies range, therefore the sensors have their self-resonance, which limits the frequency in which they can be applied (Cempel, 2001).

The accelerometers should be fixed in such way that they will not influence the arrangements performance (Morrison, 1996); as well as they should be fixed in characteristic places of the wall-element. The wall-elements must be fixed to a correct assemblage according to the input perturbations. Perturbations must be performed on object in normal operation; during experimental realization, the mounting must have the correct boundary conditions to get realistic DoF (Carpenter's, 1993).

A set of 60 wall-elements provided by a recognized brick producer in Bydgoszcz (Poland) were tested. The proprieties of all the bricks were similar: length, 250 mm; width, 120 mm; height, 65 mm; and mass, 3.5 kg. The research has been conducted to two identical set of wall-elements.

One set has a non-conformity manufacturing (using the traditional method to identify the quality of wall-elements in line-production manufacturing – visual inspection, and measurement of mass and general dimensions) and will be called fault wall-elements, W_F. The second set has approved quality, representing the nominal structural behaviour, i.e. the second set shows the reference values, W_R. A set of 90 modal tests has been developed in controlled conditions, each wall-element was tested at the principal axes (see Figure 1): *x*, longitudinal; *y*, lateral; and *z*, vertical (Bendat and Piersol, 1996; Eykhoff, 1980).

The experimental test has been performed on a freely suspended condition to each wall-element (W_R and W_F samples). Then, the wall-element 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 1,000 Hz. 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 (see the Appendix).

4. Processing and analysis results

The obtained results have been analysed with an algorithm written in two programing codes based on Matlab programing language: first, the Virtual In Operation Modal Analysis – Vioma (Kurowski, 2001); and second, the Computer System of Identification Investigations – SIBI (Martinod *et al.*, 2013). All data sets recorded are available from the authors of this paper, as an example, the data recorded from W_F and W_R are shown in Figures 2 and 3.

An adequate interpretation of the SD allows the correct identification of the poles of the system (as was explained in EMA-LSCE method). The SD exposes the characteristics of the poles, Figure 2 shows the SDs, which allows to graphically representing the poles of a wall-element when it is excited in one point – reference – and measurements are made in another one – response (Martinod *et al.*, 2012). It can be seen that the estimated poles for certain frequencies create stable vertical lines. The vertical lines are generated in the characteristic frequencies of the system; then, it is possible to affirm that the pole identifies modal parameters if (Martinod *et al.*, 2013) the pole is stable at the frequency concerned and the pole frequency appears in the characteristic frequency.

The SD exposes the characteristics of the poles (see Figure 2), which are codified with alphanumeric characters: stable pole (*s*), vibration frequency and modal vector are stable (*v*), vibration frequency and stifling are stable (*d*), only the vibration frequency is

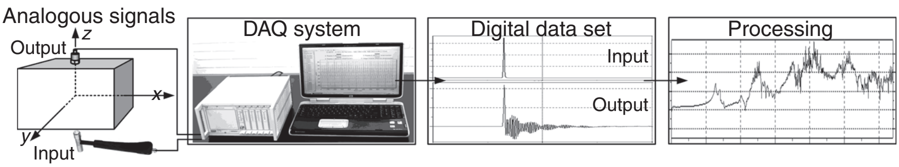

Figure 1.
Measurement flow of experimental test

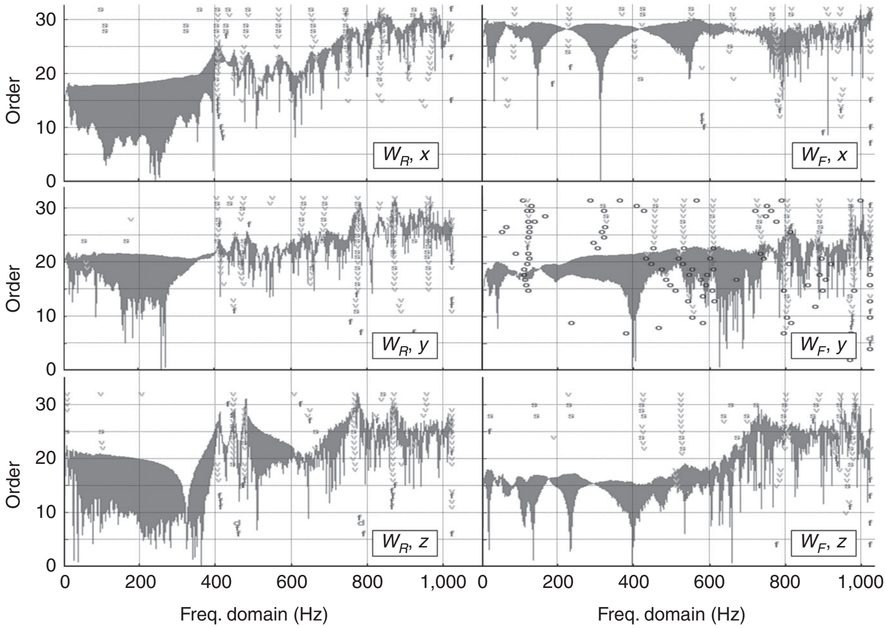

Figure 2.
Stabilization diagam (*SD*) of recorded signals

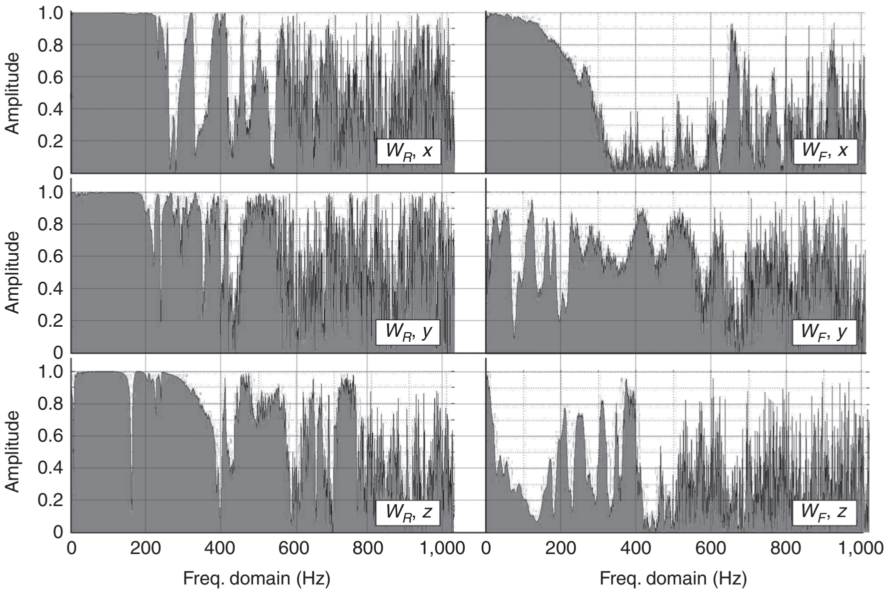

Figure 3.
$Coh_{ij}(f)$ function of recorded signals

stable (f) and unstable pole (o) (Uhl and Kurowski, 2002). Once the stable poles in the characteristic frequencies have been identified, it is possible to estimate (Uhl and Kurowski, 2002; Uhl, 2006): frequencies of the own vibrations, Ω; the damping ratio, ξ; and the modal shape, $\{\phi\}_r$.

Figure 3 shows the $Coh_{ij}(f)$ function of the accelerometers recorded signals; on one hand the data set W_R (reference wall-elements), and the other hand the data set W_R (non-conformity manufacturing wall-elements), have been processed using $EMA\text{-}Coh_{xy}$ method. In contrast with the data set W_R, the data set W_F changes (decrease) the amplitude of the function (see Figure 3).

An estimator value must be defined to synthetize the SD and Coh_{ij} information (see Figure 4) and identify the technical state of the wall-elements. The criterion for defining the estimator is the computational resources requirements (low processing cost), then the selected estimator is the area under the SDs and Coh_{ij} functions, $\{SD, Coh_{ij}\}_{(Area)}$, Figure 4 shows the estimator of recorded signals, and shows a clear difference to identify the quality of the wall-elements, due the difference of reference relative the fault wall-elements is 88.3 and 82.7 per cent to the estimator $SD_{(Area)}$ and $Coh_{ij_{(Area)}}$, respectively.

5. Conclusions and future work

The introduced results of this investigation show the existing possibility of distinguishing changes in material properties. The investigation confirmed that the application is useful as it makes possible to create SD and $Coh_{ij}(f)$ functions. The data obtained from these diagrams and functions allows assessing the state of materials by comparing their fitness.

From the obtained results, the following statement can be made:

(1) For a full fit wall-element, W_R, a stable pole can be generated in direction x at a stabilization level of 420 Hz. In case of a fault wall-element, W_F, it is not possible to generate a stable pole in the SD. The situation is the same when comparing x and y SD. This means that for W_R, a stable pole can be generated in the y-axis at a stabilization level of 790 Hz; in case of a W_F, it is not possible to generate a stable pole in the SD.

(2) For z-axis, it was not possible to generate SDs neither for good or damaged materials. The studies performed in this axis did not provide any answers and, therefore, further investigation should only be performed on the first to axis, x and y.

The estimator value $\{SD, Coh_{ij}\}_{(Area)}$ represents an appropriate index to identify the technical state of the wall-elements and to define the quality control process in a line

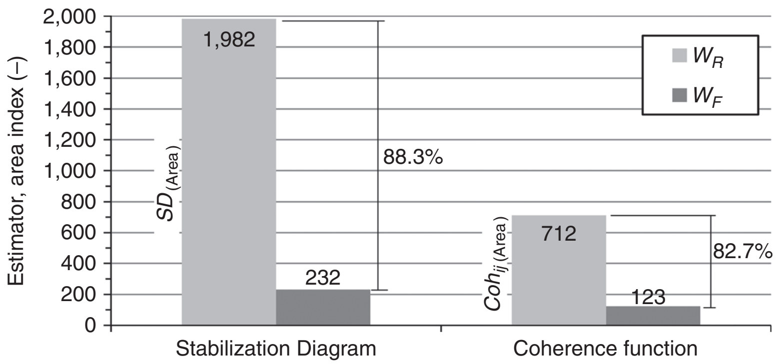

Figure 4. *SD* and $Coh_{ij}(f)$ estimator of recorded signals

production of wall-elements factory. The $\{SD, Coh_{ij}\}_{(Area)}$ can be directly normalized to get an index into the scale defined by a national structural standard.

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.

This research can be a support to structural engineers modelling buildings that had a higher resistance to earthquakes, besides, it is possible to expand the research impact taking into account the social benefit relative to earthquakes resistance.

The proposed methodology can be used to different types of wall-elements (breeze blocks, light bricks, repressed bricks, double bricks, insulating bricks, feather-edged bricks, etc.), from a quality of production perspective, the results can be used to define production tolerance ranges, then this application would be beneficial to structural engineers modelling building elements in different vibration conditions, in terms of the modes/natural frequencies of each test item by brick set so the variance of results is determined.

The paper opens to different research fields, the elements can be considered for future studies, e.g. to establish the estimator value $\{SD, Coh_{ij}\}_{(Area)}$ limit to a particular wall-element and particular national structural standard.

References

Bendat, J.S. and Piersol, A.G. (1996), *Method of Analysis and Measurement of Random Signals*, PWN, Warsaw.

Carpenter's, R. (1993), "Dynamic diagnostics in building", *Building Review Journal*, Vol. 8 No. 1, pp. 103-114.

Cempel, C. (2001), "Reduction of redundancy of symptom observation space in system condition monitoring", *Bulletin of the Polish Academy of Sciences, Technical Sciences*, Vol. 49 No. 2, pp. 267-284.

Chauhan, S., Hansen, M.H. and Tcherniak, D. (2009), *Application of Operational Modal Analysis and Blind Source Separation/Independent Component Analysis Techniques to Wind Turbines*, Brüel & Kjær Sound & Vibration Measurement, Roskilde, Nærum.

Ewins, D.J. (2000), *Modal Testing: Theory, Practice and Application*, Research Studies Press, Hertfordshire.

Eykhoff, P. (1980), *Identification in Dynamic Arrangements*, BNInż, Warsaw.

Genta, G. (2009), *Vibration Dynamics and Control*, Springer Science Business, Rome.

Giergiel, J. (2000), *Mechanical Trembling*, AGH, Cracow.

Giergiel, J. and Uhl, T. (1990), *Identification of Mechanical Arrangements*, PWN, Warsaw.

Hanson, D., Randall, R.B., Antoni, J., Thompson, D.J., Waters, T.P. and Ford, R.A.J. (2007), "Cyclostationarity and the Cepstrum for operational modal analysis of MIMO systems – part I: modal parameter identification", *Mech. Syst. and Signal Processing*, Vol. 21 No. 6, pp. 2441-2458.

He, J. and Fu, Z.F. (2001), *Modal Analysis*, Butterworth-Heinemann, London.

Kaczmarek, J. (1993), *Basis of Theory of Trembling and Dynamics of Machines*, WSM, Szczecin.

Kurowski, P. (2001), “Identification of modal models for mechanical constructions on the basis of exploitation measurements”, PhD thesis, AGH, Cracow.

Martinod, R.M., Betancur, G.R. and Castañeda, L.F. (2012), “Evaluating damping elements for two-stage suspension vehicles”, *Ingenieria. e Investigacion*, Vol. 32 No. 1, pp. 11-17.

Martinod, R.M., Betancur, G.R. and Castañeda, L.F. (2013), “Identification of the technical state of suspension elements in railway systems”, *Vehicle System Dynamics*, Vol. 50 No. 7, pp. 1121-1135.

Martinod, R.M., Betancur, G.R., Castañeda, L.F., Kałaczyński, T. and Żółtowski, M. (2013), “Estimation of combustion engine technical state by multidimensional analysis using SVD method”, *Int. J. Vehicle Sys. Modelling and Testing*, Vol. 8 No. 2, pp. 105-118.

Morrison, F. (1996), *Art of Modelling of Dynamic Arrangements*, WNT, Warsaw.

Tylicki, H. (1999), “Optimization of process of forecasting of technical state of motor vehicles”, qualifies for professorship trial of No. 86, ATR, Bydgoszcz.

Uhl, T. (1997), *By Computer Helped Identification of Models of Mechanical Constructions*, WNT, Warsaw.

Uhl, T. (2006), “The inverse identification problem and its technical application”, *Arch. Appl. Mech*, Vol. 77 No. 5, pp. 325-337.

Uhl, T. and Kurowski, P. (2002), *Vioma User’s Guide*, University of Mining and Metallurgy in Kraków Press, Cracow.

Uhl, T. and Lisowski, W. (1996), *Practical Problems of Analysis of Modal Construction*, CCATIE, Kraków.

Żółtowski, M. (2005), “Identyfikacja zagrożeń drganiowych obiektów budowlanych”, *Budownictwo Ogólne ZN ATR*, Vol. 196 No. 1, pp. 375-382.

Żółtowski, M. and Orłowicz, R. (2005), “Wybrane zagadnienia izolacyjności akustycznej stropów drewnianych”, *Budownictwo Ogólne ZN ATR*, Vol. 196 No. 1, pp. 367-374.

Appendix

Figure A1. Experimental test recorder

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