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BRIDGE SYSTEM IDENTIFICATION FOR STRUCTURAL HEALTH MONITORING

BY

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Abstract. The system identification can be defined as the process of deducting and/or updating the structural parameters relating to the dynamic data recorded through specific measurements. The structural parameters used mainly in the case of bridge structural behaviour are flexural rigidity, damping and modal parameters. The analysis of any change in these parameters helps the administrators permanently monitor the technical status of the bridge. In Romania the use of identification systems in the technical monitoring of bridges has three main advantages. First, the optimized management of the limited financial resources allocated to the maintenance and repair of the bridges is desired. Secondly, the operating life of the structure under normal conditions is extended due to the optimization of the maintenance and repair works. Finally, the fluidization of the traffic and the elimination of the waiting times that occur as a result of the rehabilitation works may be achieved by carrying out the repairs in time.

Keywords: bridge; structural health monitoring; damage detection; system identification; maintenance; repair.

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1. Introduction

In Romania approximately 1900 people lose their lives in road accidents annually and their number increases every year (European Commission, 2018). This statistic should alarm the authorities in charge, who will have to develop and implement various strategies to eliminate the main factors that favour the occurrence of the road accidents (Comisu, 2006, Research program CEEX 309, 2006).

Since the early 1980s, there has been a growing awareness on the worldwide deterioration of the transport infrastructure. In our country, as the road infrastructure ages, the evaluation of the technical state of the roads and particularly of the bridges in operation as well as the monitoring of their long-term behaviour becomes an increasingly significant topic.

An extensive research program has been developed within the Faculty of Civil Engineering and Building Services of the ”Gheorghe Asachi” Technical University in Ia□i to create a viable system of monitoring the technical state of bridges, aiming to evaluate their sustainability and viability. The technology studied is a Structural Health Monitoring (SHM) system aiming to integrate a complete identification system for modelling the structure degradation and to predict the remaining life span (Comisu, 2006).

As stated before, the Structural Identification (SI) can be described as the process of deducting or updating the structural parameters based on the dynamic measurements of the input and output data or, in some cases, only on the basis of the output data. The structural parameters considered could be rigidity, damping and modal parameters enabling the successful monitoring of the technical status of the bridge framing system.

In Romania, the research program implemented within the Faculty of Civil Engineering and Building Services in Iaşi aims to create a mobile laboratory equipped with a complete set of computing equipment and techniques and able to reach the following objectives:

– the dynamic testing of bridges using electrodynamics vibrator;

– the determination of dynamic characteristics;

– the 3D modelling of the structure of the tested bridge;

– the calibration of the calculation model;

– the permanent comparison of the characteristics recorded on the real structure to those calculated in the previous test stage;

– the timely structure diagnostics to limit the extent of the degradation;

– the application of the bridge protection protocol and the execution of the required repair work in the shortest time possible.

In Romania, the use of SI to monitor the technical status of bridges implies (Research program CEEX 309, 2006):

– the optimized management of financial resources dedicated to the maintenance and repair of road infrastructure, especially bridges;

– the optimization of maintenance and repair works leading to the extension of the operating life of the bridges concerned in order to obtain benefits that can be redirected to the investment sector;

– maintaining the bridge in a good technical condition for a long period of time, requiring only limited works of current maintenance, and thus fluidizing the traffic served by the structure.

2. Objectives for the Implementation of Bridge Identification Systems

The application of the identification systems in bridge monitoring by SHM technology presents the following general objectives (Comisu, 2006, Research program CEEX 309, 2006):

– the identification and analysis of the mechanisms that lead to the occurrence and extension of the degradation processes characteristic to bridges;

– the design and calibration of a 3D model of the bridge under monitoring to identify the degradation process type that affects the structure, position and severity of the degradation in real time. The 3D numerical model is permanently recalibrated to be in correlation with the real structure;

– the creation of a monitoring system of the SHM type needs a dense network of sensors, distributed throughout the structure. This SHM system is capable of accurately identifying the occurrence and extension of the degradation. Considering the technological evolution and the type of sensors available, it is recommended that the network of the detection nodes be wireless to facilitate data transmission and processing;

– the possibility to identify the occurrence and extension of degradation as soon as possible in order to urgently take the necessary repair measures. The decision to alarm the structure administrator and activate an intervention protocol must be based on real data, eliminating any subjectivism;

– optimizing bridge management strategies to precisely establish:

- the remaining operating time;
- the necessary repair work;
- the financial resources needed to secure the structure;

– extrapolating the obtained results and implementing the method at the level of the entire road infrastructure in operation.

The **specific objectives** of using modern systems for monitoring the technical condition of bridges can be:

– the identification of the occurrence of any major degradation process which, by its extension, could influence the technical state of the bridge;

– the monitoring system analyses the behaviour of the structure at different loads. Thus, at the most important points of the bridge, sensors are arranged in order to capture the data necessary to describe the evolution of the different parameters. The main degradations targeted are: the corrosion of the reinforcement, concrete carbonation, freeze-thaw defects, alkali-silica reaction, the structural degradation or modification of the structural behaviour (static deformation, stresses, crack opening), and change of frequency, amplitude, acceleration or vibration modes. The evolution of different degradation mechanisms can be predicted by monitoring the physical and chemical parameters of the materials of which the bridge is made (such as temperature, humidity, pH for concrete constructions or corrosion velocity of the reinforcement) and mechanical parameters (such as strains, vibrations or deflections);

– the structural identification system will enable the evaluation of the severity of the degradation process and, implicitly, the viability of the bridges.

3. Methodology for Identifying Bridge Systems

The research program developed aims to create a modern system for tracking the bridge behaviour. For this purpose, a new application methodology was developed, which contains 12 essential steps, namely:

1. Equipping the bridges with a sensor system used to determine the main stages of degradation, starting with its occurrence, then evolution and until the necessary remedial measures are taken. The sensors will collect information regarding the most important degradation processes, namely reinforcing corrosion, concrete carbonation, freeze-thaw cycles, alkali-silica reactions, mechanical degradation, changes in structural parameters (such as stresses and deformations) or modal properties (such as characteristic frequencies, deformation modes, etc.).

2. The periodic monitoring of the modal parameters, at predetermined intervals of time – recommended every year and mandatory after the occurrence of an important event in the structure life (earthquake, flooding that could lead to the erosion of the infrastructures, accidents, heavy transport, etc.). Modal parameters monitoring consists in dynamically testing the bridge with the help of a series of dynamic exercise devices, data acquisition, processing and analysis. This equipment should be installed on a mobile laboratory that can be moved periodically to monitored bridge sites (Research program CEEX 309, 2006, Mannan *et al*., 1996, Richardson *et al*., 1993).

The IT technology currently available makes it possible, both from a logistical and economic point of view, to install the entire monitoring chain on the site of the structure and to transmit the collected data to a central server. In this stage, the data are automatically processed. These technologies make the permanent monitoring of the targeted bridges possible. Moreover, the identification of the threshold level, which endangers the users, is done automatically, and therefore the structure may be closed immediately.

The non-destructive examination technology mentioned is based on the analysis of the structure vibration and it generally involves three elements:

– the dynamic bridge testing to determine modal parameters;

– an algorithm to identify the degradations, their type, location and extent;

– an algorithm to evaluate the degradation of the structure and to estimate the remaining life of the bridge.

The development of research in the field resulted in the creation of a variety of methods of signal excitation and processing. The testing procedure based on the Fast Fourier Transformation (FFT) method and the methods for estimating structure frequencies have significantly improved the accuracy and repeatability of the research. With their help, modal parameters can be identified based on input data and structural behaviour.

Modal testing methods include:

– the use of more exciters and a variety of excitations signed;

– the data acquisition and processing of input and output signals using FFT;

– the analysis of output data through several reference curves for a more accurate estimation of modal parameters;

– the modal parameters are independent of the bridge excitation and are obtained from the measurements of the frequency response functions. These systems are linear and do not depend on excitation.

3. When any change in the vibration mode of the structure is identified, the personnel in charge analyses the measurements corresponding to a series of specific functions such as: response frequency, impulse response function, power spectrum or cross power spectrum. It is known that frequency response functions and cross power spectra are measurements performed on two channels, which involve at least two sensors and two signals obtained simultaneously. A response function requires an answer signal and an excitation signal, while a cross power spectrum is formed between two response channels: the impulse response function and the automatic measurement channel, a motion sensor and a data acquisition channel (Mannan et al., 1996).

4. Periodically, the collected data are transmitted to a central server located within the administrator's monitoring centre, where the information is centralized, processed and analysed (Fig. 1). The degradation process is identified in real time as part of the new data processing. The advantages of this identification system are the following:

– bridges are monitored continuously through a multi-channel monitoring system;

– data from multiple monitoring systems can be processed by a single computer;

– each monitoring system is programmed to analyse the measured parameters exceeding the present threshold levels;

– when the alert protocol is triggered, the monitoring system urgently notifies the central server;

– further data processing, 3D model calibration and neural network processing are performed by the central server and the data is stored in its archive.

5. Based on the data collected in-situ, the personnel in charge develop a 3D model of the monitored bridge in the laboratory (Mannan *et al*., 1996, Richardson *et al*., 1993). This model helps to analyse of the structure (by means of the finite element method) and determine its response in vibrations. The force to which the bridge is subjected can be easily represented by the force vector {f(t)} defined by the formula:

$$[M]*\{\ddot{x}(t)\}+[C]*\{\dot{x}(t)\}+[K]*\{x(t)\}=\{f(t)\} \tag{1}$$

In the model specified in formula 1, the excitation forces and responses are time dependent functions (*t*), and the matrices [*M*], [*C*] and [*K*] are constant (Koh *et al*., 2003). However, analysing the given formula, it can be observed that its solutions are directly influenced by the mass, rigidity, and damping properties of the structure (Mannan *et al*., 1996).

6. In the case of the implementation of the SHM technology from the beginning of the bridge operation, the calibration of the developed 3D model in the laboratory takes place after analysing the first data collected from the site. These data come from the first dynamic test, which will be considered the T_0 moment in the bridge life. The model thus calibrated is stored in the database, being considered the ”*dynamic signature of the bridge*”.

7. Each dynamic bridge testing performed in-situ is followed by a recalibration of the studied model. At this stage, the modal properties derived from the real structure are compared with the basic properties (recorded at the initial time T_0). The changes are automatically processed by a neutral network which determines the degradation location and the affected elements, estimates.

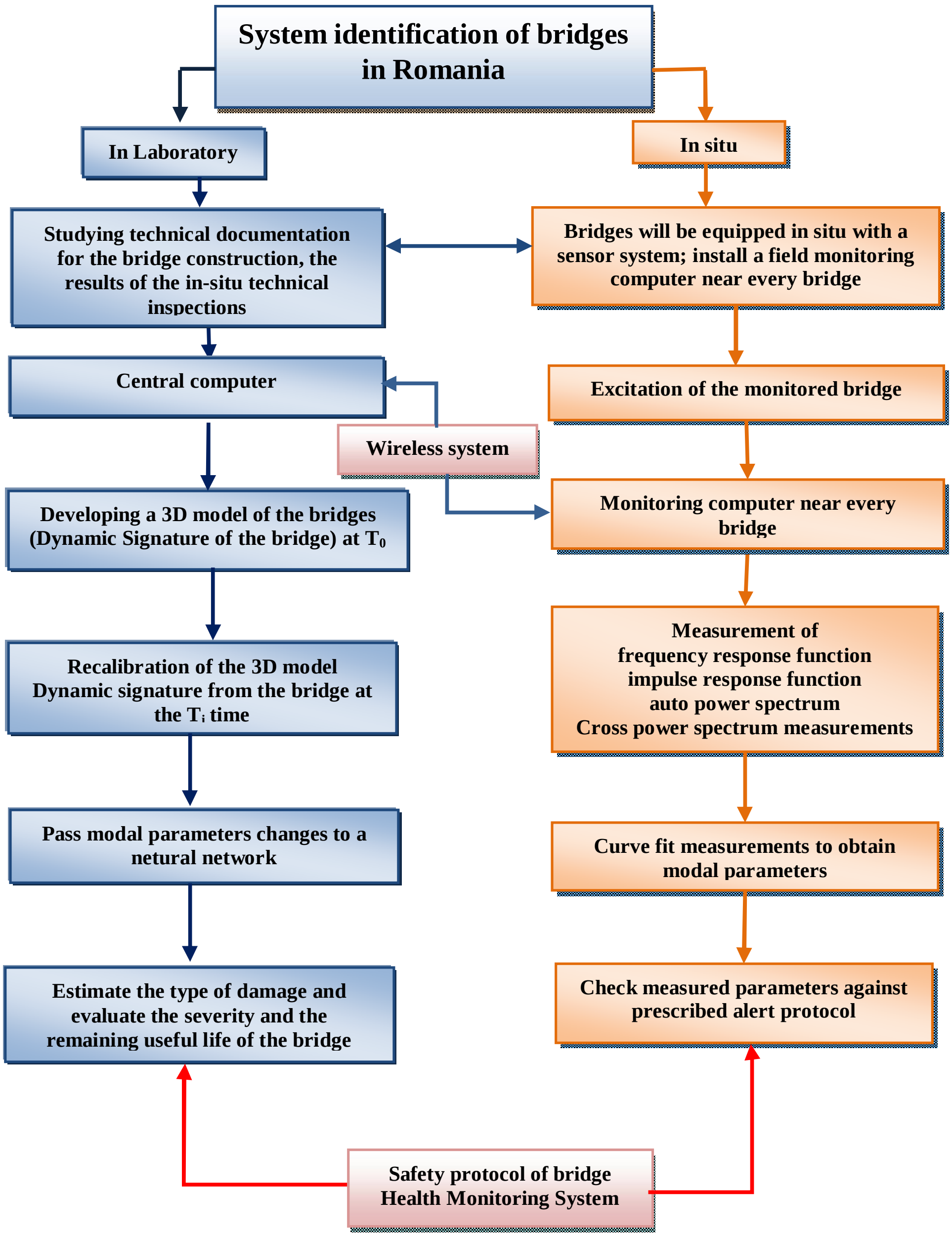

Fig 1. System identification of bridges

8. the damages that have occurred and evaluates the remaining useful life of the bridge (Fig. 1). All subsequent calibrations of the 3D model are stored in the database as the structure model from the T_i moment. They consist in checking and modifying, if necessary, the mechanical characteristics of the materials and the geometric ones. Each verification will be performed in relation to the calibrated model in the previous test phase, respectively at $T_{i\text{-}1}$ time (Haritos and Qwen, 2004, Ren and Roeck, 2002a).

9. If the monitoring of dynamic characteristics at step $\mathrm{T_i}$ does not identify significant changes from the data recorded in step $\mathrm{T_{i-1}}$, then the technical condition of the bridge is considered to be "*appropriate*".

10. The monitoring process continues in successive steps throughout the entire operating life of the bridge, until, as a result of the analysis of the data from the monitoring $\mathrm{T_z}$ stage, significant changes of the dynamic characteristics are identified in relation to the model of the bridge calibrated in the $T_{z\text{-}1}$ stage (Haritos *et al*., 2004, Ren *et al*., 2002b).

11. Each monitoring system installed in-situ is programmed to verify the recorded data and compare it with a "*threshold*" level. Whenever this level is exceeded, the system automatically sends a warning signal to the central server and to the personnel concerned.

12. In order to locate the degradation observed following the modification of the recorded modal parameters, the data analysis is using a neural network (Jang *et al*., 2002, Carbas *et al*., 2013). After solving the identified problems, the 3D model of the bridge can be used as the basic model for the training of the neural network.

13. The degree of development of the degradation process, the place on the structure where the respective degradation is manifested and its severity are found through the behavioural analysis of the calculation model stores in the database. At any time it can be estimated how degradation will evolve depending on the measures to be taken by the administrator.

This monitoring process is part of the SHM system and is a very complex subject with direct consequences on the viability of bridges in our country.

4. Conclusions

This paper presents the main features of a modern bridge identification system that utilises in-situ measuring of the modal data, an analytical 3D model of the target structure and a neural network for locating and quantifying degradation pathways.

The approach highlighted in the article, together with the traditional monitoring of other parameters, such as temperature, vibrations caused by earthquakes, the erosion of substrates due to floods, heavy transport, etc., add a new dimension to the effective monitoring of the Romanian bridge network.

In the coming years, it is expected that the structural identification technology will become a practical tool used mainly to improve the estimation of the technical state of the bridges and will be implemented at the level of each administrator and for all structures in Romania.

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IDENTIFICAREA STRUCTURALĂ PENTRU MONITORIZAREA STĂRII TEHNICE A PODURILOR

(Rezumat)

Utilizarea identificării sistemului constructiv al podurilor pentru modelarea degradărilor şi predicţia evoluţiei stării tehnice s-a bucurat de o atenţie deosebită din

partea cercetătorilor din România în ultimii ani. Identificarea sistemului poate fi descrisă ca fiind procesul de deducere şi/sau actualizare a parametrilor structurali pe baza datelor dinamice identificate în cadrul măsurătorilor specifice. Parametrii structurali utilizați cu precădere în acest caz sunt rigiditatea, amortizarea sau parametrii modali. Pe baza analizei oricăror modificări a acestora, administratorii monitorizează permanent starea tehnică a podului. În România, utilizarea sistemelor de identificare în cadrul monitorizării tehnice a podurilor are 3 direcții principale, canalizate pe principalele avantaje ale metodei. În primul rând, se doreşte administrarea optimizată a resurselor financiare limitate, dedicate înțelegerii şi reparării podurilor. În al doilea rând, creşterea duratei de exploatare a structurii în condiții normale se datorează optimizării lucrărilor de întreținere şi reparații executate, permițând obținerea prelungită de beneficii economice ce pot fi redirecționate spre alte sectoare primordiale. O ultimă direcție identificată este fluidizarea traficului şi eliminarea timpilor de aşteptare ce apar ca urmare a execuției lucrărilor de reabilitare, prin realizarea la timp a reparațiilor curente.