PROBLEMS OF DEVELOPMENT OF WIRELESS SENSORS FOR EXPERIMENTAL MODAL ANALYSIS

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Summary

Experimental identification of structural dynamics properties of large civil engineering structures usually involves application of long signal cables during the experiment. Such cables are heavy, difficult to handle and to be laid by testing engineers, as well as they are often damaged during use. That is why recently more and more often wireless sensors have been applied in modal testing of large civil engineering structures. Authors tested application of Mica2 modules with TinyOS software for PC in measurement system. Possibility of application of GPS synchronisation of measurement of multiple MEMS accelerometers was also studied. Authors present a short description of results of testing of a prototype of the developed wireless vibration measurement system in laboratory and field. The indications for future improvement of the prototype system are discussed.

Keywords: Experimental Modal Analysis, Civil Engineering, Wireless sensors.

PROBLEMY BUDOWY I ZASTOSOWANIA SIECI CZUJNIKÓW BEZPRZEWODOWYCH W BADANIACH MODALNYCH

Streszczenie

Eksperymentalna identyfikacja dynamicznych własności strukturalnych budowli wymaga zwykle zastosowania długich przewodów sygnałowych. Takie przewody są ciężkie, kłopotliwe w przenoszeniu i układaniu oraz wrażliwe na powstawanie mechanicznych uszkodzeń w czasie użytkowania. Z tych powodów ostatnio coraz częściej w badaniach modalnych budowli są stosowane czujniki bezprzewodowe. Autorzy przetestowali zastosowanie modułów Mica2 oraz oprogramowania TinyOS dla komputera PC w systemie pomiarowym. Rozważyli także możliwość synchronizacji pomiaru przy pomocy wielu akcelerometrów MEMS z wykorzystaniem GPS. W pracy zaprezentowano opis wyników testowania zbudowanego prototypu bezprzewodowego systemu pomiaru parametrów drgań uzyskane w laboratorium i na rzeczywistym obiekcie. Wskazano kierunki doskonalenia zbudowanego prototypu systemu pomiarowego.

Słowa kluczowe: Eksperymentalna Analiza Modalna, diagnostyka obiektów budowlanych, czujniki bezprzewodowe.

1. INTRODUCTION

Some of the Civil Engineering (CE) structures focus attention of engineers who investigate dynamics of systems due to specific shape and/or size. The considered group of structures that are referred to by the authors as the large ones, comprises: skyscrapers, stadiums, bridges, tunnels, dams, towers, masts, antennas, tall factory chimneys and large elastic foundations. All of the mentioned objects possess considerable compliance what makes them susceptible to external loads that cause both static and dynamic deflections. Depending on the type of the structure it might be subjected to effect of: wind, water current as well as waves, ground movement (micro-seismic phenomena) and various kinds of forces induced by traffic. Deflections caused usually by a composition of the listed above loads may produce problems with a proper service of such the structures (large static deformation, high amplitude vibration) and sometimes even their irrevocable damage due to the occurrence of excessive stresses. The branch of the system dynamics that deals with elastic deflection resulting from dynamic loads is called structural dynamics [1]. Generally, the way a structure vibrates depends on properties of the materials, dimensions and the way the structure is connected with its environment (boundary conditions). Sometimes in engineering practice other effects like change of the properties of materials due to variation of loads as well as temperature distribution as well as variations have to be also considered. The most common way of taking into account the structural dynamic parameters of large CE structures is determination of these properties by numerical simulation during the design process. As there exist some uncertainties dealing with: values of material properties, dimensions, properties of connections of various elements of the structures as well as of the boundary conditions it is very common to investigate the structural dynamic properties experimentally in a procedure of system identification based on vibration measurement. Additionally, nowadays, more and more often parameters of structural dynamic models are being used as the base of condition monitoring and/or diagnostics [2]. The experimental system identification technique aiming at determination of the structural dynamic properties is called Experimental Modal Analysis (EMA) [3, 4, 5].

2. EXPERIMENTAL MODAL ANALYSIS OF CIVIL ENGINEERING STRUCTURES

The direct aim of EMA is estimation of natural frequencies ω_r, modal dampings (damping ratios) ξ_r and mode shapes ψ_r, $r=1, 2, \dots, n$ [4]. These three types of parameters are elements of the modal model of a system under consideration and they do not depend on the excitation F(t).

Usually the spatial distribution of mass, damping and stiffness is being described in practice by certain (quite a large number in case of Finite Element Method use) amount of lumped elements.

Determination of the modal model is physically equivalent to a transformation of a lumped parameter (mass, damping and stiffness) dynamic system to a set of independent oscillators

The experimental techniques of determination of the modal model base on definition of the dynamic compliance H(ω), that is a ratio of the Fourier transform X(ω) of response signals x(t) to the Fourier transform F(ω) of the excitation F(t). It might be determined basing on results of simultaneous measurement of the excitation forces F(t) and responses x(t) to these excitations [3, 4, 5].

$$\mathrm{H}(\omega)=\frac{\mathrm{X}(\omega)}{\mathrm{F}(\omega)} \tag{1}$$

On the other hand, the dynamic compliance H(ω) depends on modal model parameters [4] in the following way:

$$H_{ik}(j\omega)=\sum_{r=1}^{n}\left(\frac{p_r\psi_{ri}\psi_{rk}}{j\omega-\lambda_r}+\frac{p_r^{*}\psi_{ri}^{*}\psi_{rk}^{*}}{j\omega-\lambda_r^{*}}\right) \tag{2}$$

$i, k = 1, 2, \dots, N$
where: p_r - a r-th constant scaling coefficient.

Assumptions of the EMA comprise: linearity, Maxwell reciprocity, stationarity and low or proportional values of damping coefficients [4].

The traditional approach to the experimental identification of modal parameters consists in excitation of a single mode shape at a time. Usually the harmonic excitation forces are used. In case of the CE structures:

- for slender, tall structures (like masts or chimneys) the sudden release of elastic cords attached to the object in a way corresponding to maximum amplitudes of deflections of mode shapes under investigation may be practiced,
- for bridges the sudden release of loading masses suspended under the bridge may be practiced.

The mentioned techniques of modal testing base on analysis of damped free vibrations of the tested objects for their actual boundary conditions.

In engineering practice of EMA usually Phase Separation Method (PSM) [5] - commonly identified with EMA is used. During the experiment the response to wide frequency band excitation forces (impact, broad band white noise or swept harmonic ones) is measured along with the excitations. The parameter estimation techniques [3, 4, 5] that assure effective discrimination of the mode shapes which were excited during experiments are precise but considerably sophisticated and that is why the estimation has to be computer assisted. The PSM method is widely applicable in engineering practice in laboratory conditions as well as in the industrial environment, if only there exists possibility to measure excitation forces. There are at least three examples for which measurement of forces is technically difficult, if possible at all. These are cases of modal testing of: means of transportation during motion, rotating parts during motion or, the last but not the least, CE structures in service.

Let us focus attention on the CE structures. There exist specialized testing facilities like European Laboratory for Structural Assessment [6] or Building Research and Consultancy [7] where full scale structural testing of buildings and/or bridges is carried out. The use of such the facilities is limited in case of large CE objects partly since they cannot be moved as a whole to the testing facilities and partly due to difficulty of replaying of the tested structure real (field) boundary conditions during the laboratory testing.

In the field conditions, in which CE structures are typically structurally tested, initiation of their appropriate vibration constitutes quite a serious problem. Demand of use of considerable values of amplitude of the excitation forces during testing, which is a consequence of substantial mass and stiffness of large CE structures, causes that the actual excitation amplitude values have to be rather calculated than precisely measured in case of application of large impact devices (a dropped mass) [8] or unbalance mass exciters [8] that are attached during testing to the tested structure. Additionally, preparation to such tests is time consuming, so that the required interruption in service of the tested structures limits the applicability of the mentioned excitation techniques.

Faster development of EMA of large CE structures followed the change of the attitude of the testing engineers to the necessity of measurement of excitation forces during testing. The Operating Deflection Shape (ODS) [9] analysis, practiced in mechanical engineering, started to be applied to analysis of results of vibration testing (the technique was referred to as Basic Frequency Decomposition [10]) of CE structures that were subjected during service to environmental (wind etc.) or operational (traffic etc.) loads. The considered technique was inappropriate for identification of the close (in frequency) mode shapes. This drawback was overcome partly with introduction of operational Least Squares Complex Exponential (LSCE) modal parameter estimation algorithm [11], the tool of Operational Modal Analysis (OMA). Later CMIF [4] or Frequency Domain Decomposition [10] parameter estimation technique was introduced, but the real breakthrough in structural testing of large CE structures came with application of stochastic subspace identification (SSI [12]) estimation technique [8]. The most effective in use proved to be Balanced Realisation (BR) algorithm. The SSI algorithms are superior to other ones as they tolerate some nonstationarity of measured signals and might be effective even when some modes are excited only occasionally.

The problem of efficient testing corresponds to the excitation force spectrum. Majority of modal parameter estimation methods assume white noise ambient excitation what is not always achievable in engineering practice. That is why the application of sophisticated estimation methods like SSI or operational PolyMAX [13] does not compensate the general drawback of their use i.e. identification only of mode shapes that were actually excited during the experiment and that were appropriately represented in the recorded signals as a result of the type of spectrum of excitation forces present during experiments. By the way, due to unmeasured excitations the identified mode shapes are not scaled and their scaling requires usually carrying out of an additional experiment [14].

Testing of large CE structures becomes more and more applicable nowadays. First, the experimental modal model is used for validation of results of numerical calculations. EMA is the only way of determination of structural parameters when no validated numerical structural dynamics (usually FE) model is available. Additionally, more and more often modal parameters are being used for condition monitoring (occasional or permanent) of large CE structures [15].

Selected examples of investigation of structural dynamics properties of CE structures comprise testing of: skyscrapers [16], stadiums [17, 18], bridges [19, 20, 21], tunnels [22], and large elastic foundations [23].

Structural testing of CE structures might base on: relative displacement, absolute acceleration or strain measurement [15].

There are three important problems of modal experiment carried out on large CE structures:

- how to apply appropriate sensors,
- how to transfer measured signals to the dynamic signal recorder or analyzer,
- how to carry out analysis of the recorded signals and make the results accessible.

The vibration sensors used for structural dynamics testing of large CE structures are usually the seismic accelerometers to assure appropriate accuracy of measurements in low frequency range (<10Hz). The sensitivity of the used accelerometers varies from 0.1 V/m/s2 (piezoelectric sensors, 0.5Hz÷2kHz of measuring frequency range and mass of 0.21 kg [24]) up to 250 V/m/s2 (capacitive sensors, 0÷50Hz of measuring frequency range and mass of 7 kg [25]). The sensors have to be resistant to the operational conditions encountered during field type of testing. The properties of the sensors should not vary considerably with change of environmental conditions (e.g. temperature) and time, what altogether makes the appropriate vibration sensors quite expensive devices.

Presently, transfer of the measured signals consists usually in the analogue type of transmission via a signal cable that connects a sensor to a recorder/analyzer. In case of large CE structures this technique cause many problems. Long signal cables are difficult to be laid and then removed after testing. They are susceptible to mechanical damage due to forces applied by the testing engineers as well as caused by the own weight of the cables. Some loss of measuring signal energy occurs during transmission via long cables and the motion of cables along with a tested structure may induce electrical distortions to measuring signals.

There exists a need to carry out many structural tests of various objects in a relatively short period of time what indicates that the applied measurement system should be mobile to be easily transferred from one object to another [15]. There is also a problem of minimising of power consumption of the measurement system, important in the field conditions.

Finally, when application of vibration parameters in condition monitoring or Structural Health Monitoring (SHM) systems is considered the price of the measurement system should be minimised, the signal transmission distortion should be kept low and remote as well as easy access to the signal records should be assured.

One of the factors that contribute considerably to progress in structural testing of large CE structures is the wireless technology.

3. WIRELESS TECHNOLOGY IN PRACTICE OF DYNAMIC MEASUREMENT

Direct benefit of application of Wireless Measurement Systems (WMS) is an increase of number of the measuring points and simplification of measuring systems due to cable length reduction.

The authors focused on development of a wireless accelerometer based measuring system. The properties of the typically used accelerometers are discussed in [26].

In order to identify parameters of the structural model it is necessary to record extensive data-set of structural response. Currently, these data sets are collected by expensive wired and powered data acquisition systems, which consist of one central unit with fixed number of channels. Each channel is connected to one sensor by wired connection acting as ‘antenna’ for all electrical noise common in industry environments. Data acquisition system consists of signal conditioning, data storage unit and power supply. The time for set up of wired system can take 2-3 weeks in case of large structures [27].

Wireless measurement systems can reduce cost of the whole system due to low cost per channel and simplification and freedom of sensor placements. The general block diagram of classic and wireless measurement solution is presented in figure 1.

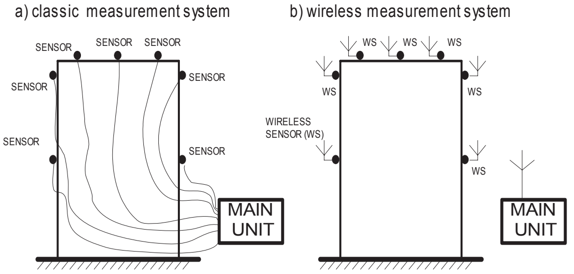


Fig. 1. Block diagram of classic and wireless measurement system.

There are still many important problems concerning application of WMS, which are being investigated. Some of them like: a set of sensors organization, data synchronization or energy consumption are discussed briefly in following subsections.

3.1. Wireless measurement system sensor topology

There are two standard network topologies widely used in practical implementation of WMS [28]:

- Star topology – uses one of the node as a central base station, which communicates directly with each sensor in the network. This topology needs small software overhead during protocol development but, at the same time, it reduces distance between sensors and requires higher energy consumption for the whole network. With this topology it is relatively simple to design an accurate synchronization technique. Finally, this topology enables fast replacement of standard measurement system to wireless solution.
- Mesh topology – enables to design large sensor networks with small energy consumption, distributed over the structure, but requires difficult structure of communication protocol and synchronization technique. This kind of network structure is suitable for SHM purposes.

The described above network topologies are shown in figure 2.

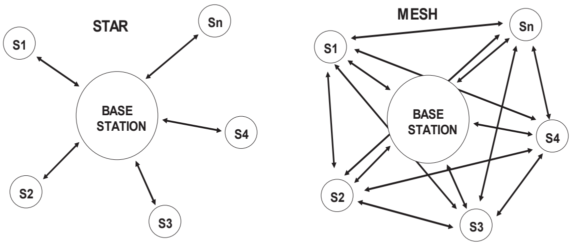


Fig. 2. Star and mesh topology of wireless measurement system.

3.2. Wireless measurement system synchronization methods

Precise data synchronization mechanism in WMS must be implemented for further proper parameter estimation. Difference in phases of measured signals may lead to considerable errors of modal parameters estimation. There are several methods for data synchronisation:

- distributed synchronization – that bases on distribution of reference time over the sensor network. There are few possible realizations of this method like: network time protocol NTP [29], reference broadcast synchronization RBS [30], timing-sync. protocol for sensor networks [31] and time diffusion protocol TDP [32],
- ‘post-facto’ synchronization – that bases on calculation of the transfer time between sensor and base station and further data synchronization at the base [33],
- GPS based solutions – that bases on precise time synchronization at the sensor node by Pulse Per Second (PPS) signal and time information received from serial output of the GPS receiver [26, 34].

The choice of the synchronization method depends on many additional factors like:

- required power consumption – the least power consuming method is the ‘post facto’ synchronization, which enables to achieve accuracy in the order of ms,
- network topology – the distributed synchronization gives the good results in mesh based sensor networks but this method requires high energy consumption,
- synchronization accuracy – the GPS solution the best synchronization accuracy gives the best synchronization accuracy within few µs but requires satellite signal source and higher power consumption.

In the measuring system developed by the authors the ‘post-facto’ synchronization and GPS synchronization mechanisms were implemented.

3.3. Energy consumption

One of the most important parameters of WMS is overall energy consumption. In case of large scale SHM systems located over the structure the energy consumption should be as low as possible, allowing of years of active operations. In case of vibration measurement systems there is great potential of energy harvesting from the vibrating object [35], in case of outdoor systems it is possible to use solar energy or wind energy. Harvested energy is transformed to electrical energy and stored in batteries. The energy consumption highly depends on applied hardware and software, so great care should be taken during design of wireless systems operating for years.

In case of measurement for EMA of CE applications the problem of energy consumption is less important, because high capacity batteries or AC mains energy may be applied.

The developed by the authors wireless sensor was powered from high energy battery.

4. PROBLEM DEFINITION AND PROPOSED SOLUTION METHOD

Basing on analysis of problems of application of EMA to large CE structures and properties of available wireless signal transmission techniques the authors decided to develop and implement a WMS which:

- assures correct estimation of modal parameters,
- is easy applicable to EMA of large CE structures,
- has a low energy consumption.

In this section two developed solutions are reported.

4.1. Measurement system based on MICA2 modules with TinyOS

The general view of the first considered wireless system [36] that was intended to be used on CE objects is presented in the figure 3.

The reported solution uses MICA2 wireless modules as sensors nodes of the star topology wireless network. The sensor software was developed using TinyOS operating system, enabling data acquisition, storage and transfer. The data synchronization was achieved using ‘post facto’ technique.

The developed MoteViewer application was running on PC over the wireless base station that controls synchronization and proper data transfer from sensors.

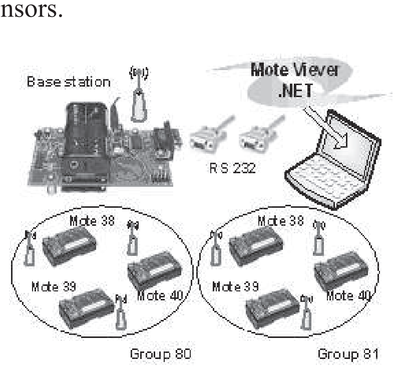


Fig. 3. General scheme of first WMS for testing CE objects.

Wireless modules enable acquisition of 20 seconds long vibration signal with frequency of 200 Hz. The limitation of the storage time comes from FLASH memory applied on MICA2, the sampling frequency is also limited to 200Hz due to software overhead of TinyOS operating system. A measured signal coming from an Oceana Sensors [37] integrated accelerometer with 10g measurement amplitude range is sampled on the module by 10 bit AD converter and saved in flash memory. After reception of all samples data can be transferred over the radio to the base station for synchronization with data coming from the other sensors, and then analyzed.

The results of the first tests of the measuring system prototype were unsatisfactory. The analysis of the recorded data showed that the measured signals had great noise level at 25 Hz and measured amplitude was very small comparing to full scale of A/D converter. The source of noise at the 25 Hz comes from flash write procedure and its high influence to amplifier built inside the applied accelerometer. This unwanted feature was difficult to overcome due to completed electronic circuit and lack of additional accelerometer documentation. The small amplitude of the signal and poor parameters of A/D converter (actual resolution of 8 bits) implemented on MICA2 caused additional problems with proper signal analysis. The authors decided to design and implement their own wireless sensor which is briefly described in the next subsection.

4.2. Developed measurement system based on GPS synchronization

The diagram of the second WMS developed by the authors is presented in figure 4. The base module of the system contains acquisition board equipped with: ATmega 128 controller, 4 Mbit flash memory, 9 independent channels of 16 bit resolution A/D converters, a temperature sensor, adjustable low pass filters and supply circuits for controllers, filters and sensors. The base module allows connecting a 16LVS GPS signal satellite Garmin receiver.

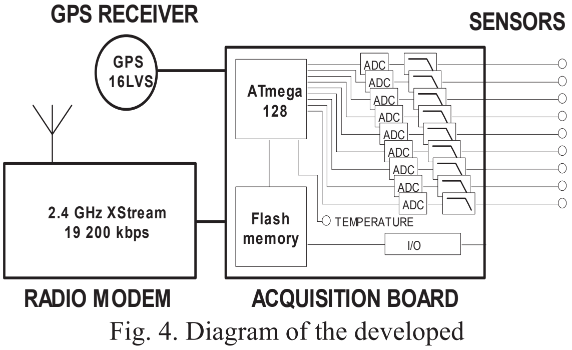


Fig. 4. Diagram of the developed WMS.

Serial output of the GPS sensor is used for time reception and the digital input PPS signal is used for ±1 µs synchronization of the modules over the network. As a radio module the XStream 2.4GHz OEM radio modem from MaxStream [38] was chosen. The parameters of the radio module allow user implementation of different network strategies and supply long range data transfer up to 180 m for indoor and 16 km for outdoor applications. The maximum data transfer achieved by the applied radio modem is 19.200 kbps, which is sufficient for the presented application. The applied sensors from Oceana Sensors [37] have integrated amplifiers with voltage output and sensitivity of 1000 mV/g with 4 g maximum acceleration amplitude.

The maximum current consumption of the complete WMS is equal to 250 mA and with applied battery pack of 5000 mA capacity allows for 20 hours of continuous operation. The maximum sampling frequency of the module is 500 Hz. The module was also equipped with specially developed T–LC noise cancellation filter for sensor supply. First test on the structure showed that obtained metrological properties are sufficient for testing carried out on CE objects. The general view of the developed wireless sensor is presented in fig. 5.

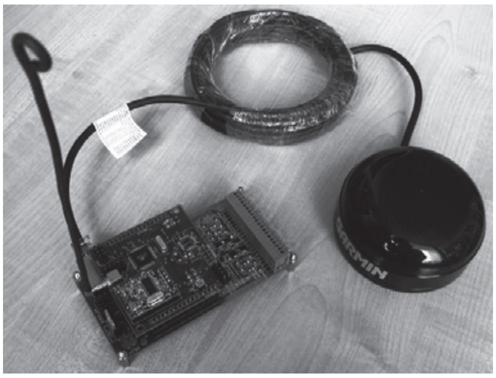


Fig. 5. Picture of developed WMS.

5. ASSESSMENT OF PERFORMANCE OF THE PROTOTYPE WMS

The testing of the prototype of the developed measurement systems consisted of three stages:

- comparison of the measurement results obtained with use of a set of wireless sensors with each other as well as with a reference acceleration sensor,
- comparison of values of modal parameters estimated basing on the simultaneous measurement carried out with use of a set of wireless sensors and a set of standard accelerometers.
- a trial measurement aiming at identification of modal model of a bridge structure.

For recording of signals provided by the used standard accelerometers the multi-channel LMS SCADAS III dynamic signal analyzer was used.

5.1. Comparison of measurement results in the time domain

Checking the data synchronization between sensors was the main purpose of the first stage of testing. The experiment was done for a set of three sensors. The sensors were attached to an electrodynamic shaker and excited with 30 Hz sinus wave. The results of comparisons of time signals and estimated spectra are presented in fig. 6.

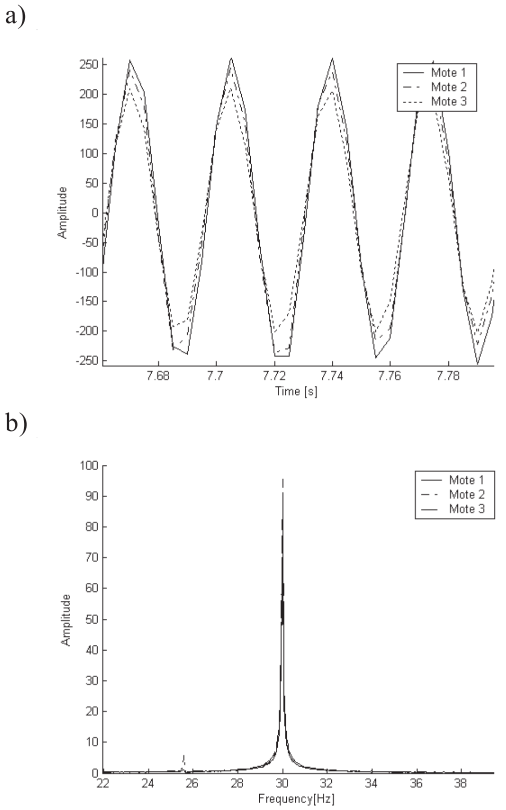


Fig. 6. Comparison of time signals (a) and of amplitude spectra (b).

The recorded time histories of all wireless sensors and of the reference signal correspond each other. There was found no phase shift between signals measured by various sensors what proved appropriate properties of the measured signals for application in EMA.

5.2. Modal analysis of laboratory test frame

The aim of experiment carried out during the second stage of testing was to estimate modal parameters of the object presented in figure 7 using OMA technique basing on measurement done with use of the developed WMS.

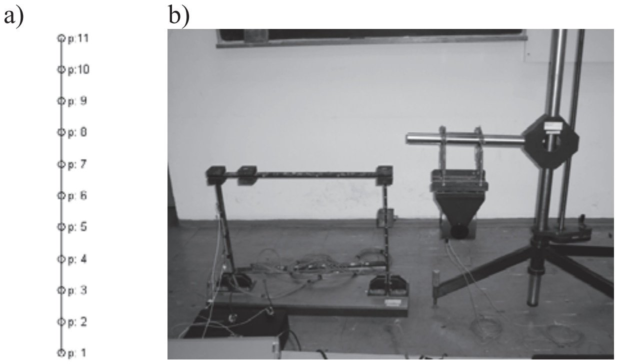


Fig. 7. a) geometry of measured object, b) experimental setup

The excitation signal (provided by electrodynamic shaker) was a frequency band limited (0÷200 Hz) white noise. The testing was composed of the two following experiments:

- experiment for MICA2 sensors,
- experiment for WMS based on GPS synchronization.

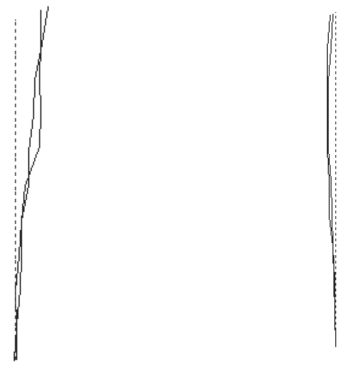
The first experiment was completed in 5 measurement runs. During each run the time signals were recorded. The sensors were placed at different locations during each measurement run. For estimation of modal parameters BR OMA algorithm implemented in VIOMA [39] toolbox was used.

The results of the 1st experiment are presented in table 1, examples of estimated modes shapes are presented in figure 8. The comparison between mode shapes was done with use of Modal Assurance Criterion (MAC) [4].

Table 1. Modal parameters of laboratory test frame estimated during the 1st experiment.

Wireless sensors		MAC [%]	Piezoelectric accelerometers	
Natural frequency [Hz]	Modal damping ratio [%]		Natural frequency [Hz]	Modal damping ratio [%]
10.96	2.36	90	11.22	3.96
25.50	0.17	---	---	---
---	---	---	37.71	1.66
43.89	0.72	95	44.06	0.78
51.06	0.35	---	---	---
59.43	2.52	88	59.89	2.58
82.09	0.51	---	---	---

The analysis of results of the first experiment showed that, in case of application of MICA2 sensors, the performance of the implemented A/D converter was unsatisfactory for precise representation of acceleration in the recorded data.



ω_1=10.96 Hz

ω_4=43.89 Hz

Fig. 8. Examples of mode shapes of test frame estimated during 1st experiment.

There appeared also a problem with insufficient sensitivity of the used sensor. For the mentioned reasons the resultant quality of estimation of modal parameter was poor.

The problems encountered during the first experiment of testing made the authors improve the developed WMS. The improvements consisted in: use of GPS synchronization, application of a better A/D converter and accelerometers of higher sensitivity.

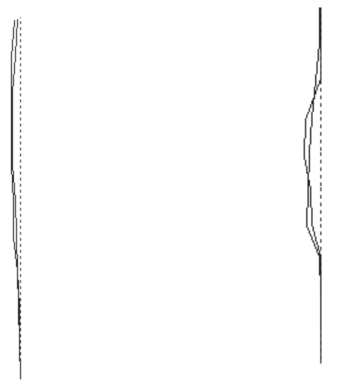
The results of second experiment are presented in table 2. Examples of estimated modes shapes are presented in figure 9.

Table 2. Modal parameters of laboratory test frame estimated during the 2nd experiment

Wireless sensors		MAC [%]	Piezoelectric accelerometers	
Natural frequency [Hz]	Modal damping ratio [%]		Natural frequency [Hz]	Modal damping ratio [%]
11.07	3.18	90	10.96	2.77
43.81	0.97	95	43.92	0.77
59.60	2.52	95	59.63	2.09
81.58	1.58	47	82.24	2.10
118.91	0.50	79	119.30	0.26
121.33	0.31	51	121.24	0.32
158.58	0.30	75	158.28	0.32
159.95	0.28	33	160.53	0.26

Analysis of the results presented in table 2 shows that all mode shapes of system present in the considered frequency range were estimated properly. The relatively high differences in the compared estimated modal damping ratios values are common in practice of EMA. At current stage of the considered WMS development the authors are convinced that the results of the second stage of testing proved its applicability to EMA.

The additional experiment was carried out on the tested frame.



ω_2=43.81 Hz

ω_5=118.91 Hz

Fig. 9. Examples of mode shapes of tested frame estimated during the 2nd experiment.

Higher amount of measuring points was used during the additional experiment. The enhanced geometry of the tested object is showed in figure 10.

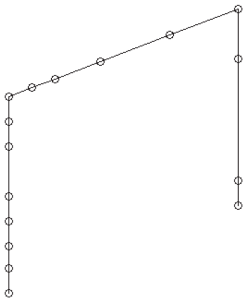


Fig. 10. Geometry of measured object.

The results of the additional experiment are presented in table 3.

Table 3. Modal parameters of laboratory test frame.

Wireless sensors		MAC [%]	Piezoelectric accelerometers	
Natural frequency [Hz]	Modal damping ratio [%]		Natural frequency [Hz]	Modal damping ratio [%]
43.91	0.64	95	43.85	0.78
59.74	2.29	98	59.68	2.41
118.71	0.60	97	118.89	0.61
155.88	0.57	94	155.49	0.48
159.28	0.78	86	158.53	0.49

The achieved level of correspondence of modal parameters obtained with use of signals measured by the developed WMS and by the applied standard measuring system was considered to be satisfactory.

5.3 Modal analysis of a single bridge span

The last stage of testing of the developed WMS was modal experiment carried out on one span of a bridge. The measuring set-up during the testing is showed in figure 11.

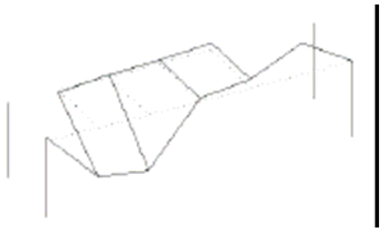
Fig. 11. Measuring set-up during modal testing of a bridge span

Values of the estimated natural frequencies and modal damping coefficients are listed in table 4. The example of the estimated mode shapes is presented in figure 12.

Table 4. Modal parameters of a span of a bridge.

Wireless sensors		MAC [%]	Piezoelectric accelerometers	
Natural frequency [Hz]	Modal damping ratio [%]		Natural frequency [Hz]	Modal damping ratio [%]
2.16	18.68	30	1.84	3.77
3.16	5.47	58	3.16	2.76
5.24	3.43	33	5.43	2.52

a) 5.24 Hz



b) 5.43 Hz

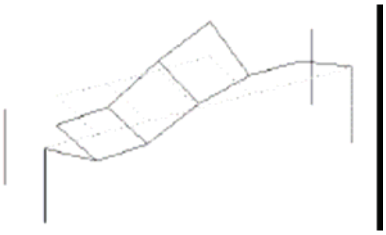


Fig. 12. An example of identified mode shapes (a) wireless test, (b) traditional test

The obtained results of modal identification were compared with results obtained (a year earlier) with use of the standard measuring system. In the considered frequency range 3 mode shapes were identified. Two of them possess high qualitative resemblance to results obtained with use of the standard measuring system.

One pair of compared natural frequency values consists of almost equal values. Nevertheless at the moment the results of the both considered tests are not sufficiently consistent to fulfill the demand of correct parameter estimation due to low correlation of the identified mode shapes. There is a variety of reasons that might cause the obtained inconsistency of results. Some of them are: application of low cost sensors that are not suited to accurate measurement at low frequency range (problem of a large constant value of spectrum amplitude), limited excitation forces arising during the testing due to traffic jams, low number of sensors applied what caused necessity to carry out five partial experiments, ambient temperature and humidity variation. The authors plan to repeat the testing with use of the more sophisticated sensors

On the other hand when demand of easy applicability is considered the used WMS proved to be very convenient in use. The main benefits of use of the system covered: easy placement of necessary cabling (to connect sensors to the base modules), no need to pass any cables across the roadway as well as no need to use any extra power supply. Some problems were caused by relatively slow rate of radio transmission of collected data to computer after the measurement. This becomes important when during modal tests the base modules should be used many times due to necessity to perform a set of partial experiments. The optional direct wire connection (RS) of the modules to a computer was implemented in each module to overcome this problem when necessary.

The energy consumption of the measurement system proved to be small during the carried out experiment. Majority of the initially stored energy was still available in batteries after the test.

Finally, it should be noted that the developed WMS was positively assessed be the modal testing engineers. The idea of use of modules connected by cables with sensors located nearby proved to be convenient for application in modal testing. In the opinion of the authors such a solution is not the best choice in case of use for the condition monitoring purpose, when capability of each sensor to transfer the data in a wireless way to the computer seems to be very useful.

6. SUMMARY

Preliminary assessment of performance of the prototype wireless measurement system proved its applicability to experimental modal analysis of large civil engineering structures. Application of wireless transmission technology makes it applicable also for condition monitoring (SHM) purpose.

The proposed solution the time synchronisation problem based on GPS signal is very accurate and offers independence of the synchronization from the sensor network topology.

It seems to be possible still to lower the power consumption of the developed sensors to make them more convenient in applications to condition monitoring. One of the suggested research directions consists in optimization of the necessary time for power down and wake up period of the GPS sensor in order to keep synchronization time under the specified value.

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