Wireless and stand-alone measurement system for dynamic identification of structures

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ABSTRACT: This paper contains a study about a wireless Bluetooth measurement system useful in order to control the accelerations on great dimensions structures. The structure on which they have been carried out is a steel structure with rectangular plan. On the upper level there has been installed a vibrodine for generating a sinusoidal force for dynamic characterization of the structure.

The realized measurement system utilizes a datalogger and some accelerometer; they communicate among themselves through wireless Bluetooth protocol, which allows to cover distances up to 100 m.

The datalogger is a common PC equipped with a module for Bluetooth communication. The accelerometers are constituted by: 1) a triaxial acceleration sensor, with adjustable range among the following values \([1.5, 2, 4, 6]\) g; 2) a gyroscope with input range of 150 degrees/second; 3) a microcontroller, with analogue to digital converter with maximum sampling frequency of 610 Hz, which samples the signals and manages the device; 4) a class 1 Bluetooth module which allows the communication over universal platform; 5) a 860 mAh battery.

The datalogger is equipped with a software developed in LabView environment; it is able to simultaneously acquire acceleration’s samples from every accelerometer and to obtain in real time plots of accelerations, speeds and displacements and to save the samples in binary files for successive processing.

The experimentation has been finalized to the calibration of the numerical model to guarantee the structure functionality and also to study the structure behaviour under dynamic actions generated by wind. This experimental activity concurred also to discover modal shape not easily recognizable also using a corrected dynamics analysis.

1 CASE STUDY
1.1 Introduction

This paper contains a study about a wireless accelerometer measurement system particularly useful for controlling the dynamic response on great dimensions structures.

This system has been prepared in order to assess the dynamic behaviour of a new realization steel structure which, for further needs of the commissioner, has had several modifications during the realization stage both as regards loads and shape and dimension of structural elements. In order to assess the mechanical characterizations and main vibration periods of the structure some dynamic tests have been performed by equipping the structure with wireless accelerometers and undertaking it to external forces of harmonic type generated by a vibrodine placed on the floor of roof. The dynamic characterization activity of the structure has been developed for two main goals. The first one regarded the need of guaranteeing the integrity of an external glazed wall of cladding by controlling the relative displacements among the thin columns on the building sides, the second one was to study of the piers behaviour of facade
frame. The analysis has, in fact, allowed to assess the effective restraint grade imposed to piers by box beams displaced in horizontal way with sun-shading function. Such assessment has permitted to establish the verifications performed during the plan stage referring to the critical load.

1.2 Description of the structure

The structure has a strongly lengthened rectangular plant with 6 and 35 meters sides. Its height is about 22 meters and it shows a different distribution of the piers on two principal sides. It is realized in adjacency to an existent building. It has a great number of very thin piers on the external facade specifically realized in order to support glazed panels. On the other side, in adjacency with the existent building, there are braced piers while, on four corners there are four piers of bigger dimensions having stiffness function of the whole structure.

The great dimensions of the building would have required a control system with a great cabling development in order to transfer the information to the datalogger. Then, the fixing of the accelerometers at the top of columns would have required great times with difficult over-ground works. The utilized system, instead, beside to be wireless, it is formed by light weight accelerometers which has permitted a rapid application on elements with the same epoxy resins.

In order to analyse the structure, a finite elements model has been performed. The structural elements, beams, piers, have been modelled with mono-dimensional elements. The purlins, bridles, diagonals and truss uprights of roof have been restrained by internal hinges, and also the beams of floor of roof have the restraint of simple support on lateral beams.

In order to simulate the existence of the floor of roof in reinforced concrete and the floors on middle storeys, bidimensional elements have been utilized in concrete of 5 cm thickness. We have noticed in this modelling that the floor is able to give a great stiffness to the storey by better dividing the seism and wind thrusts on vertical structures.

2 EXPERIMENTAL ACTIVITY

2.1 The force system

For the structure stress a force system has been predisposed consisting in a vibrodine which function principle is based on the rotation of two plates in contraposition, where masses have been aligned in order to explicate a variable horizontal force with sinusoidal law respect to the central axis of the same machine.

The harmonic force generated by the vibrodine brings accelerations on the structure as taller as the force frequency is moving closer to natural frequencies of the system. The experimentation for such force type has a result strictly connected to the accelerometers sensibility since for the low force frequency, the vibrodine applies a weak force, so we read on the structure rather low assesses of the accelerations. In such way, the utilized acquisition system, which can be calibrated under different levels of sensibility, is better for structures with high natural frequencies. In the case in exam, for low assesses of accelerations, the acquisition system has shown some overcoming limits in the function that the first vibration ways are essentially translational along the main axis and rotational in plan.

2.2 Data acquisition system

The utilized measurement system has wireless connectivity capability, using Bluetooth protocol: it is constituted by a central unit, necessary for managing distributed sensor network and a set of smart sensors, which communicate through Bluetooth protocol.

Central unit is equipped with Bluetooth interface, till 100 m, capable of simultaneously acquiring acceleration samples from all the accelerometers. Utilized software, developed in LabView environment, allows to obtain in real time acceleration graphs and to save samples in binary files for successive processing.

Acceleration sensors are triaxial type: each one has a triaxial accelerometer, a gyroscope in the range of ±150 degree/second and a class 1 Bluetooth module, for robust communication on an universal platform. Technical characteristics of sensors are:
- Selectable channels for sampling (X, Y, Z and rotation);
- Battery status indication;
- Device status LED;
- Tunable input range (1.5 g, 2 g, 4 g, 6 g);
- Tunable thresholds for accelerometer, gyroscope and battery;
- Selectable sampling rate, 610 Hz max;
- 860 mAh lithium battery.

Central unit is managed with a software developed in LabView environment, graphic development environment distributed by National Instruments. Steps for network management are summarized in flowchart in Figure 3. In Figure 4 there is front panel of management software.

2.3 Main characteristics of use and upgradeability of the system

The accelerometer utilized for implementing wireless measurement system are low cost capacitive micromachined accelerometer; features signal conditioning, a 1-pole low pass filter, temperature compensation and g-Select which allows for the selection among 4 sensitivities.

X and Y measurement axis has 350 Hz -3 dB frequency bandwidth and Z axis 150 Hz. With input range of 1.5 g have 800 mV/g sensibility, while with 6 g the sensibility is 200 mV/g. Noise root mean square value in the frequency range 0.1 Hz – 1 kHz is 4.7 mV.

![Figure 1: Prospect of the structure and angular particular.](image1)

![Figure 2: Vibrodine utilized for the force system.](image2)
Figure 3: Flow chart of the software for measurement management. - Phases of positioning of accelerometers at the top and along the height of piers and detail of sun-shade joint – pier

Figure 4: Accelerometer on a pillar and front panel of measurement management software.
Acceleration analog signal must be digitalized to be transmitted via Bluetooth; a microcontroller, with 10 bits analog-to-digital converter, that is 1024 quantization levels, is employed. It results that theoretical quantization noise is 2 mg; actually, effective quantization noise is 5 LSBs (Least Significant Bits), and thus minimum measurable acceleration level is 10 mg. Due to limitations of Bluetooth protocol, maximum sensor number in a Bluetooth network, called piconet, is 7 units plus the controller. It follows that, in order to have wider number of sensors, every 7 sensors a controller is necessary. The number of Bluetooth receivers usable with a PC (Personal Computer) depends exclusively on the available USB port number and they can be away increased with the use of a simple hub; therefore, the number of sensors usable with a single system is unlimited for practical purposes. It is worth noting that system cost remains low, since, apart from PC cost, the cost of system with 6 sensors is comparable to that of a PC and the costs of Bluetooth receiver and USB hub are very low. Main limitation of the present system is linked to maximum distance among receiver and sensors: theoretical maximum distance is 100 m, without barriers. Practically, max distance is reduced to about 50 m, without barriers. Possible solution to this issue, in case that one or more dimensions of the structure to be monitored is wider than 50 m, is that of using several PC, connected among themselves through Wi-Fi (Wireless Fidelity) wireless protocol: in this way, with the use of directional antennas, distance of some kilometres are covered. Every PC receives data only from subset of sensors, placed at distance less than 50 m. For instance, graphs of acceleration, speed and distance, in time and frequency domain, related to a pillar, are reported. From these graphs is simple to determine also transfer functions for analyzed quantities.

2.4 Bluetooth technology

Bluetooth uses a radio technology called frequency-hopping spread spectrum, which chops up the data being sent and transmits chunks of it on up to 79 frequencies. In its basic mode, the modulation is Gaussian frequency-shift keying (GFSK). It can achieve a gross data rate of 1 Mb/s. Bluetooth provides a way to connect and exchange information between devices such as mobile phones, telephones, laptops, personal computers, printers, Global Positioning System (GPS) receivers, digital cameras, and video game consoles through a secure, globally unlicensed Industrial, Scientific, and Medical (ISM) 2.4 GHz short-range radio frequency bandwidth. A master Bluetooth device can communicate with up to seven devices in a Wireless User Group. This network group of up to eight devices is called a piconet. A piconet is an ad-hoc computer network, using Bluetooth technology protocols to allow one master device to interconnect with up to seven active devices. Up to 255 further devices can be inactive, or parked, which the master device can bring into active status at any time. At any given time, data can be transferred between the master and one other device, however, the devices can switch roles and the slave can become the master at any time. The master switches rapidly from one device to another in a round-robin fashion. (Simultaneous transmission from the master to multiple other devices is possible, but not used much). The Bluetooth specification allows connecting two or more picnets together to form a scatternet, with some devices acting as a bridge by simultaneously playing the master role in one piconet and the slave role in another.

Many USB Bluetooth adapters are available, some of which also include an IrDA adapter. Older (pre-2003) Bluetooth adapters, however, have limited services, offering only the Bluetooth Enumerator and a less-powerful Bluetooth Radio incarnation. Such devices can link computers with Bluetooth, but they do not offer much in the way of services that modern adapters do. Any Bluetooth device will transmit the following information on demand: 1) Device name; 2) Device class; 3) List of services; 4) Technical information, - device features, manufacturer, Bluetooth specification used, etc... Any device may perform an inquiry to find other devices to connect to, and any device can be configured to respond to such inquiries. However, if the device trying to connect knows the address of the device, it always responds to direct connection requests and transmits the information shown in the list above if requested. Use of a device's services may require pairing or acceptance by its owner, but the connection itself can be initiated by any device and held until it goes out of range. Some devices can be connected to only one device at a time, and connecting to them prevents them from connecting to other devices and appearing in inquiries until they disconnect from the other device. Every device has a unique 48-bit address. However these addresses are generally not shown in
inquiries. Instead, friendly Bluetooth names are used, which can be set by the user. This name appears when another user scans for devices and in lists of paired devices. Most phones have the Bluetooth name set to the manufacturer and model of the phone by default. Pairs of devices may establish a trusted relationship by learning (by user input) a shared secret known as a passkey. A device that wants to communicate only with a trusted device can cryptographically authenticate the identity of the other device. Trusted devices may also encrypt the data that they exchange over the airwaves so that no one can listen in. The encryption can, however, be turned off, and passkeys are stored on the device file system, not on the Bluetooth chip itself. Since the Bluetooth address is permanent, a pairing is preserved, even if the Bluetooth name is changed. Pairs can be deleted at any time by either device. Devices generally require pairing or prompt the owner before they allow a remote device to use any or most of their services. The protocol operates in the license-free ISM band at 2.4-2.4835 GHz. To avoid interfering with other protocols that use the 2.45 GHz band, the Bluetooth protocol divides the band into 79 channels (each 1 MHz wide) and changes channels up to 1600 times per second. Implementations with versions 1.1 and 1.2 reach speeds of 723.1 kbit/s. Version 2.0 implementations feature Bluetooth Enhanced Data Rate (EDR) and reach 2.1 Mbit/s. Technically, version 2.0 devices have a higher power consumption, but the three times faster rate reduces the transmission times, effectively reducing power consumption to half that of 1.x devices (assuming equal traffic load).

2.5 Dynamic research and estimate of modal parameters

In order to assess the main dynamic parameters of the structure useful for giving an answer to problems regarding the global behaviour under horizontal actions, as well as saving the integrity of the glazed facade and assess the restraint grade given by sun-shades to piers in facade, the piers have been monitored in some points. Firstly, the accelerations of six piers on the main prospect have been monitored by positioning the accelerometers in the mid-span section of piers placed between two sun-shading beams of better light. Secondly, only one pier has been monitored by placing the accelerometers along its vertical development in order to assess the transversal displacements of the element useful for determining the elastic line of the pier.

Twenty-seven tests have been performed, twenty-one of them with parallel force at Y axis (the long side of the structure) and six with parallel force at X axis (the short side of the structure).

Vibrodine speed data have been chosen in a way functional to the verification of the structure model, goal of the measurement work. In particular, firstly some preliminary tests have been performed, imposing to the vibrodine a variable rotation speed from supported minimum data to maximum ones, trying not to damage the structure, of course. Then, we have verified by real time measurements which force speed determines an important stress of the structure; having chosen the most important force frequencies, we have recorded all signals.

Among tests with force parallel to Y axis (long side), we can see in the tables that one which provokes a bigger stress of the structure is that in which the vibrodine speed is 289 rotations per minute; in it, the maximum displacement provoked to the monitored nodes of the structure is 6.2 mm, obtained in the central pier. It needs therefore to notice that, in correspondence of this test, the relative displacement among central piers is not higher than 3.2 mm. Then, we can obtain the relative maximum displacement in the test in which the vibrodine speed is 290 rotations per minute, that is 4.2 mm, lower than assesses compatible with the fixing system of glazed panels that is equal to about 10 mm.

As regards to the tests performed by force parallel to X axis, we notice that we can have the absolute maximum displacement of the structure nodes at the speed of 129 rotations per minute and that of the floor is 4.8 mm.
3 NUMERICAL ANALYSIS

3.1 Finite elements model and correlation with experimental parameters

Following are some deformations obtained by results of the dynamic analysis developed on calibrated model downstream of the experimental search. We have found that the FEM model, already utilized in linear analysis, gives results very coherent to experimental results, in terms of period, obtained on the structure. The modal shapes are also well representative of the real structure behaviour. The obtained results are in perfect harmony with the experimental proofs.

For the grade of restraint supplied by sun-shades to piers on the principal prospect, we have found that they give a high grade of joint, giving a shear type behaviour.

![Figure 5](image)

Figure 5 : Graphs of acceleration, speed and displacements, in time and frequency domains.

<table>
<thead>
<tr>
<th>Reading to inverter</th>
<th>Rotations/minute</th>
<th>Frequency f</th>
<th>Period T</th>
<th>Angular speed</th>
<th>Loads on vibrodine</th>
<th>Mass</th>
<th>Generated force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Rots/min]</td>
<td>[Hz]</td>
<td>[s]</td>
<td>[rad/s]</td>
<td>[kg]</td>
<td>[kg]</td>
<td>[kg]</td>
</tr>
<tr>
<td>10.0</td>
<td>100</td>
<td>1,667</td>
<td>0.60</td>
<td>10.47</td>
<td>67</td>
<td>6.83</td>
<td>183.50</td>
</tr>
<tr>
<td>15.0</td>
<td>150</td>
<td>2,500</td>
<td>0.40</td>
<td>15.71</td>
<td>67</td>
<td>6.83</td>
<td>412.87</td>
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<tr>
<td>20.0</td>
<td>200</td>
<td>3,333</td>
<td>0.30</td>
<td>20.94</td>
<td>67</td>
<td>6.83</td>
<td>733.99</td>
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<td>25.0</td>
<td>250</td>
<td>4,167</td>
<td>0.24</td>
<td>26.18</td>
<td>67</td>
<td>6.83</td>
<td>1146.86</td>
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<tr>
<td>30.0</td>
<td>300</td>
<td>5,000</td>
<td>0.20</td>
<td>31.42</td>
<td>67</td>
<td>6.83</td>
<td>1651.47</td>
</tr>
</tbody>
</table>

Table 1: force generated by the vibrodine

<table>
<thead>
<tr>
<th>Vibrodina speed</th>
<th>floor roof</th>
<th>Central SX</th>
<th>Central</th>
<th>Central DX</th>
<th>External SX</th>
<th>External DX</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.7</td>
<td>1.2</td>
<td>1.1</td>
<td>2.1</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>105</td>
<td>1.6</td>
<td>1.9</td>
<td>1.3</td>
<td>2.5</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>110</td>
<td>2.8</td>
<td>2.5</td>
<td>1.6</td>
<td>2.8</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>120</td>
<td>2.7</td>
<td>3.0</td>
<td>1.5</td>
<td>2.3</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>289</td>
<td>1.9</td>
<td>5.4</td>
<td>6.2</td>
<td>5.9</td>
<td>6.0</td>
<td>5.1</td>
</tr>
<tr>
<td>290</td>
<td>2.3</td>
<td>4.8</td>
<td>5.6</td>
<td>5.8</td>
<td>4.9</td>
<td>4.7</td>
</tr>
<tr>
<td>292</td>
<td>2.0</td>
<td>3.7</td>
<td>3.2</td>
<td>3.5</td>
<td>3.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 2: displacement of piers (mm) found for force in parallel direction axis Y (long side)

![Figure 6](image)

Figure 6 : Modal deformations for the first three principle periods $T=1.35s$ $T=0.82s$ $T=0.73s$
4 CONCLUSIONS

Downstream of experimentation we can notice that the measurement system have given a great contribution to the calibration of the calculation model by which we have studied the displacements and stress of the structure under different actions types.

The structure during the experimental activity has provided a rather linear result by also confirming the validity of elastic parameters utilized in the model.

Then, from a point of view of the structural behaviour, the structure has answered well to horizontal actions showing a great collaboration among supporting elements. The relative displacements among piers on the principal prospect have been contained into 4 mm. We have noticed that these assesses are close to those of the calibrated calculation model that represents, in careful way, the global behaviour of the building under seismic action and wind action.

Definitely, we can say that the utilized measurement system, by the right solution, is useful for measurements, for the dynamic characteristic of the civil structure. In the performed experimentation it was not necessary to control the angular accelerations that the measure system allows to do; such further parameters permit additional details in the study of great dimensions civil structure.

REFERENCES

IEEE Draft Standard for Information Technology- Telecommunications and information exchange between systems- Local and metropolitan area network- Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications. (This document reflects the combining of the 2003 Edition of 802.11 plus the 802.11g, 802.11h, 802.11i and 802.11j Amendments) (Revision of IEEE Std 802.11-1999) (Superseded by P802.11-REVma_D8.0) 2006
