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Low-cost Structural Health Monitoring System for Smart Buildings

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***Abstract*—Structural Health Monitoring (SHM) is a discipline that aims to implement damage identification strategies through the measurement and processing of various data collected from systems under investigation, such as acceleration, temperature, displacement, force, strain, and many others. The identification of damages is strictly related to the change of dynamic properties of the structure such as natural frequency, damping rate, and mode-shapes. Synchronized measurements are mandatory to calculate these parameters, and for such reason most of the monitoring systems nowadays consist of single or multiple acquisition nodes surrounded by analog transducer networks. However, this strategy has two drawbacks, the high cost of the equipment and the usage of long dedicated cables. To solve these problems, a full-digital system has been developed. It makes use of digital MEMS accelerometers connected in daisy-chain through a digital bus implemented on an Unshielded Twisted Pair cable. The proposed solution simplifies the cabling, reduces the cost of the system, and provides accurately synchronized signals.**

Keywords — Bridge monitoring; Building monitoring; Digital Network; Low-cost sensors; MEMS accelerometers; Structural Health Monitoring.

I. INTRODUCTION

In recent years, SHM techniques [1], [2], [3], [4] gained a high importance in the field of maintenance of civil structures, industrial plants, and machines. The attention of the researchers is focused on the development of automatic damage detection algorithms capable of pointing out the presence of abnormal structural behavior, exploiting the information acquired by sensors placed on the monitored structures. A number of these approaches is based on operational modal analysis [5], [6] performed on the signals acquired by a distributed sensor network installed on the monitored structure, as in [7]. In other cases, a forced stimulus is applied for performing modal analysis. The general purpose of these strategies is that potential incoming damage can be detected with a change in the dynamic properties of the system, such as stiffness variation, resulting in a shift of resonance frequencies, or mode-shapes modification. Therefore, the continuous extraction of these features is fundamental in the maintenance of civil structures through SHM approaches.

In modal analysis techniques, the exact temporal alignment in the measured signals is mandatory, and therefore a direct analogical link from sensors to a centralized acquisition is a widely used solution. Cabling and installation may be one of the major costs in this case. The monitoring system of the Meazza Stadium (Milan, Italy) [8], for example, is divided in four sub-systems due to the huge dimensions of the structure: sensors, network nodes, ethernet network and a “master” PC. The measurements synchronization is fundamental in processing a global modal analysis or tracking certain events based on time-domain analysis. The synchronization of the four acquisition nodes, where compactRIO devices by National Instruments (NI) are employed, is provided by a trigger generated by a central unit and transmitted to all nodes by a dedicated cable. In another case, Palazzo Lombardia (Milan, Italy) [9], the monitoring system consists of a single central data acquisition system (NI-compactRIO) linked to all sensors (24 accelerometers and 10 inclinometers) installed on the structure. Since the building is a high-rise structure (161 meters height), this strategy requires extremely long and expensive cables to connect all the transducers to the central acquisition system. In [10], two historic masonry towers have been equipped with a monitoring system measuring accelerations on the top of the buildings: the instrumentation included 3 piezoelectric accelerometers, a data acquisition system (NI-9234 and NI-compactDAQ chassis) and a local PC. In [11], a suspension bridge in southern China is equipped with a monitoring system measuring the accelerations of the entire structure. The architecture is based on a single data acquisition node surrounded by an analog transducer network: due to the huge length of the main span of the bridge (about 848 m), each transducer needed an extremely long dedicated cable. Other solutions based on GPS have been employed but they are not suitable for networks installed inside buildings, where the GPS signal may be absent. All these techniques have three main drawbacks: high cost of the equipment, difficulty of synchronization, and usage of long dedicated cables for triggers and communication.

In this paper, a novel idea is proposed to simplify the installation and to guarantee the needed synchronism between the acquired data, based on a local digital bus to collect data acquired by several peripheral boards. An extensive description of the proposed solution is presented in Section II. In Sections III and IV an experimental measurement and related results are described, while in Section V some application cases for the proposed solution are presented. Finally, conclusions are summarized in Section VI.

II. Acquisition System

The proposed SHM system aims to overcome the previously mentioned issues by leveraging a distributed architecture. A block diagram of the proposed system is shown in Fig. 1. The acquisition system is composed by two main parts: an Interface Board (IB) and a network of Acquisition Nodes (AN), connected to the IB by means of the A^2B bus [12], [13].

The purpose of the AN is to collect the sensor signals and to send them to the IB. The AN are connected in daisy-chain [14] and each one integrates a low-cost digital Micro Electro-Mechanical System (MEMS) triaxial accelerometer (Fig. 2). These two features help to reduce the complexity and the length of the cabling with respect to a traditional star topology. In addition, the wire is a single Unshielded Twisted Pair (UTP), which can provide both power supply and data, thus furtherly reducing the cost. A single network of AN can accommodate up to 10 AN and a maximum number of sensors signals equal to 32 at the sampling frequency of 48 kHz [15]. As it can be seen in Fig. 1, the maximum distance between two adjacent AN is 15 m, while the total length of the network is 40 m, thus allowing to distribute the AN for example in a building floor.

Since these lengths may limit the field of application of the proposed SHM system, the IB was developed to receive data from several AN networks (up to 4) and to convert them to an ethernet format. The realized IB can be seen in Fig. 3. Many IBs can be connected through ethernet cables, thus exploiting, for example, the existing Local Area Network (LAN) infrastructure. In this way, the sensor network can be considerably extended preserving its time-synchronization properties. Alternatively, the IB can transmit the data also through USB for short distances.

Another benefit of the proposed architecture is the synchronization of the devices. In fact, the digital bus allows keeping synchronized all the AN of the network, with minimal latency and very low jitter levels [16]. Moreover, it is possible to temporally align the clock signals of the AN (with a resolution of about 20 ns) to compensate for the latency of the propagation through the nodes.

Finally, it must be pointed out that the proposed SHM system is modular and scalable. In fact, up to 10 AN can be added in a single network and if more AN are needed, an IB can acquire up to 4 networks. In addition, by exploiting the LAN infrastructure it is possible to further increase the dimension of the system by distributing the IBs.

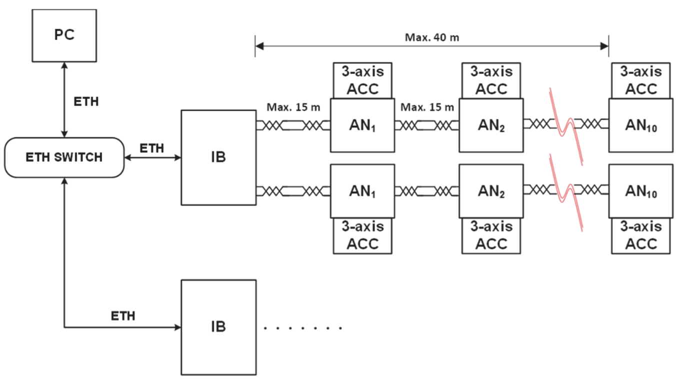

Fig. 1: Block diagram of the proposed system.

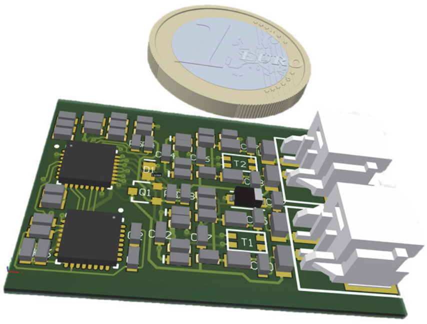

Fig. 2: Acquisition node integrating a triaxial MEMS accelerometer.

Fig. 3: Interface board.

III. Experimental Measurements Setup

Forced-response modal analysis was performed on a truss model made of two H-beams of 4.2 m length and several aluminum rods. A front view of the 3D CAD model of the structure is shown in Fig. 4. One can note the measurement layout in correspondence of the red markers.

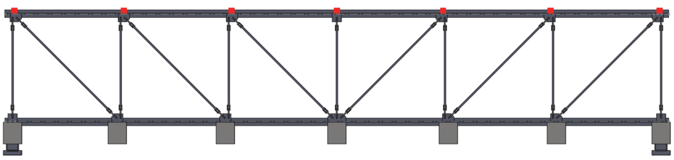

Fig. 4: Truss model.

The block scheme of the measurement is shown in Fig. 5. One can note the seven piezo-electric accelerometers connected to the analog acquisition system in a star topology and the seven digital Acquisition Nodes (AN) integrating a MEMS accelerometer each, connected in daisy-chain to the Interface Board (IB). Both analog and digital acquisition systems were connected to a PC via USB.

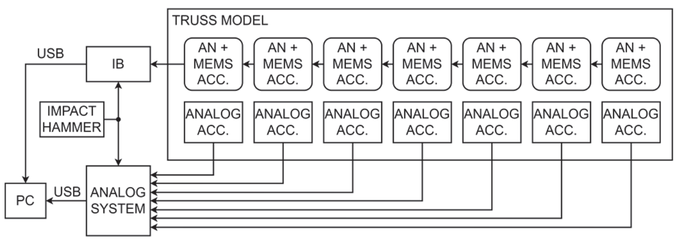

Fig. 5: Measurement diagram.

The system was excited along the vertical direction (Z-axis) with a series of impulses provided to the structure with an impact hammer, Bruel&Kjaer (B&K) type 8202, having a sensitivity of 0.99 pC/N, connected to a charge amplifier, B&K type 2635. The output of the charge amplifier was split in two lines, one going to the analog system, and the other going to one of the two analog inputs present on the Interface Board, thus allowing to record the same reference signal of the impact hammer with both systems.

The response of the structure was recorded simultaneously with a standard analog system and with the proposed full-digital solution. The analog system consisted in three National Instruments 9234 boards and seven ICP piezoelectric accelerometers, five mono-axials and two tri-axials, having a sensitivity of 100 mV/g and a full-scale value of +/- 50 g. The digital system was made of one Interface Board, connected to a PC via USB, operating at fs = 48 kHz, and seven Acquisition Nodes connected in daisy-chain. Each AN integrates a tri-axial MEMS accelerometer, having a full-scale value of +/-16 g and 14-bits digital output. The piezoelectric and the MEMS accelerometers were positioned on the structure side-by-side. Each system recorded synchronously both the impact hammer reference signal and the accelerometers signals. Since we were mainly interested in the information along the vertical axis, only the Z direction of each triaxial accelerometer was measured. Hence, a total number of eight signals was recorded by each system.

IV. Experimental Measurements Results

In Fig. 6, the auto-spectrum of the force impulse generated by the impact hammer is shown in the frequency range from 0 Hz to 1 kHz. The acceptable frequency range of the measurement is limited by a reduction of -20 dB in the impact hammer response, which corresponds to a reduction of an order of magnitude. Hence, the acceptable frequency range is comprised in the range 0 Hz – 650 Hz.

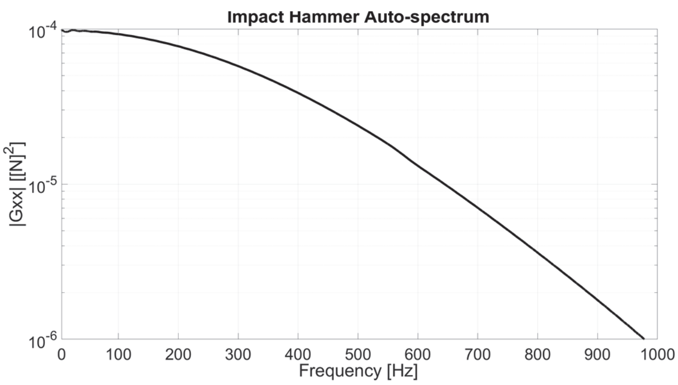

Fig. 6: Impact hammer auto-spectrum.

The Frequency Response Functions (FRF) between the impact hammer and the accelerometers were calculated for both measurements. In Fig. 7, the magnitude (above) and the phase (below) responses are shown for the accelerometer in the position 2. It is possible to note an excellent similarity of the curves in the whole frequency range of interest.

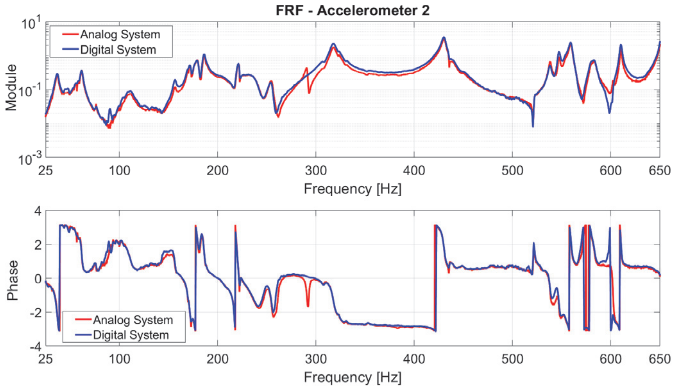

Fig. 7: Transfer function between impact hammer and accelerometer, analog system (red) and digital system (blue).

Then, an experimental modal analysis has been performed using a poly-reference least-squares complex frequency-domain method [17] and the stabilization diagram was calculated from the accelerometer FRF, for both analog and digital measurements. The aim of the analysis is the identification of the first two modes of the structure; hence the frequency range was limited from 25 Hz to 70 Hz. In Fig. 8, the result is shown for the digital measurement. One can note that the two main modes are correctly identified.

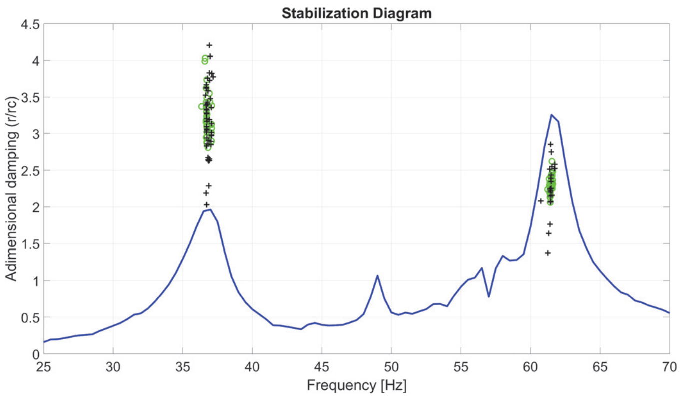

Fig. 8: Stabilization diagram for digital measurement (green marker: stable poles, black marker: unstable poles)

Then, the structural model of the first two modes was calculated and it is shown in Fig. 9. One can note an excellent superimposition of the reconstructed curve over the experimental one.

Eventually, the first two modal frequencies were calculated on the analyzed accelerometer, for both analog and digital measurements. Results are summarized in Table 1.

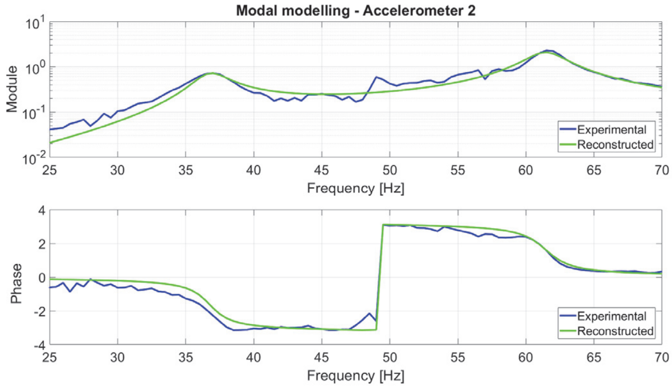

Fig. 9: Modal modelling on digital accelerometer 2.

TABLE 1: FIRST TWO MODAL FREQUENCIES CALCULATED ON ACCELEROMETER N.2 FOR ANALOG AND DIGITAL SYSTEMS

	First mode [Hz]	Second mode [Hz]
Analog System	36.7	61.6
Digital System	36.9	61.6

The mode shape is the most sensitive modal parameter to data synchronization since point movements and directions are strictly linked to phase in measurements. Therefore, mode shapes of the data obtained from both acquisition systems have been processed and compared through the Modal Assurance Criterion (MAC). MAC index can be interpreted as the normalized correlation coefficient between two vectors, and it allows detecting the similarity between two modes [18]. The MAC values are comprised between zero (no correlation) and one (perfect correlation). In Fig. 10, the MAC values show a perfect match between the first and second mode shapes detected by the two acquisition strategies.

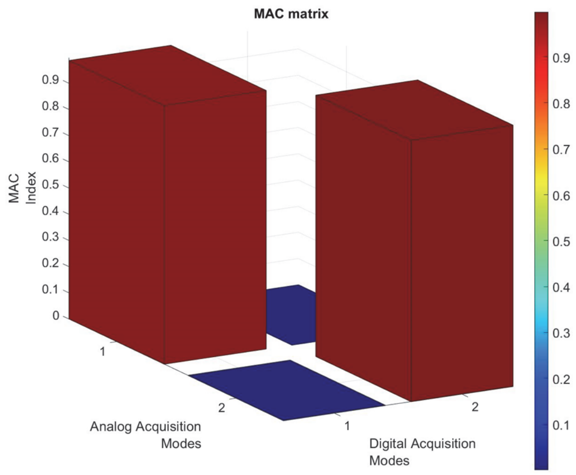

Fig. 10: MAC matrix between mode shapes processed from both data acquisition strategies.

V. Possible Applications

The proposed system can be employed for performing a vibration based SHM of civil buildings, as suggested in Fig. 11. In case of multiple floors, it is possible to use the ethernet LAN network infrastructure to include additional Interface Boards and Acquisition Nodes, thus extending the system capabilities.

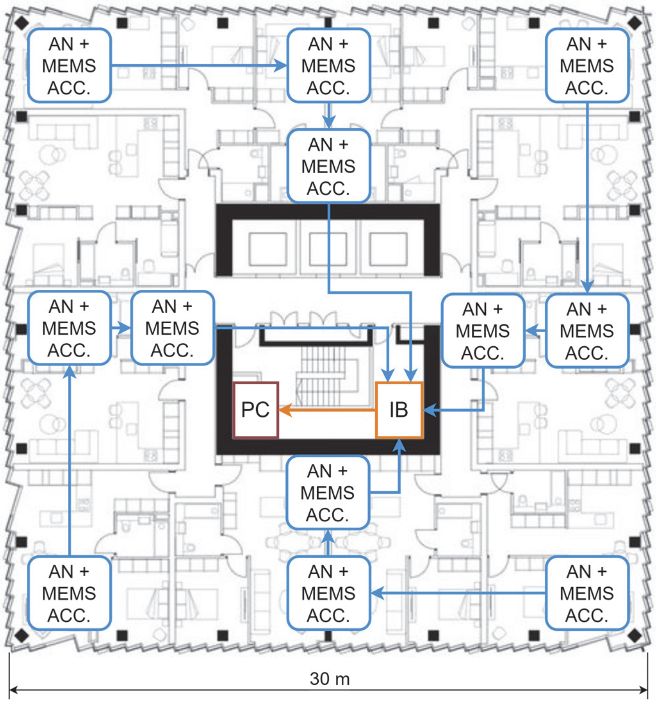

Fig. 11: Scheme of the proposed solution (orange wire: LAN connection, blue wire: digital subnet over UTP).

If the maximum distance between an IB and another IB or between the IB and a PC is longer than 100 m (which is the limit of the ethernet over CAT5 cables), there are two possible solutions: using an ethernet switch to regenerate the signal every 100 m or using an ethernet to fiber converter and transmit data using an optical fiber link.

As an example, we now describe the monitoring system installed in Palazzo Lombardia (Milan, Italy), showing the advantages of the proposed technology in a real case. In that case, the installed monitoring system consists of a central acquisition node that constantly measures all the analog transducers displaced over the entire structure (161 meters in height): 24 accelerometers and 10 inclinometers are placed on floors B3 (foundations), 9, 30, 37 and on the roof. Since the data acquisition system is installed on the 30th floor, most of the transducers required an extremely long and expensive cabling. With the proposed acquisition system, a series of Interface Boards (IB) could be located on the structure, one on each monitored floor, and connected to the data acquisition computer by ethernet cables. Then, transducers on the same floor can be hooked up to the IB with multiple A^2B daisy-chains. In this way, the installation and the architecture of the monitoring system is greatly simplified and the cost of the equipment, as well as the cost and the length of the cabling, are considerably reduced. Besides, our solution employs a full digital network, therefore increasing the rejection of the noise that is usually picked up by long analog cabling in an environment crowded with other electrical cabling and devices (power grid, appliances, air conditioning, etc.).

The proposed system is also suitable for monitoring infrastructures like long bridges (Fig. 12). Most of the monitoring systems for this type of structure rely on two main strategies. The first one makes use of a single data acquisition node surrounded by a transducers network: the drawbacks are the employment of long and expensive cables and extremely complex cable management. The second one includes multiple acquisition nodes distributed along the structure: in this case the drawbacks are the data synchronization between different acquisition nodes and a relevant increase in the equipment cost due to the high cost of each acquisition node. The proposed system provides an important step in the designing of monitoring systems for such structures since these issues are avoided. Moreover, the monitoring system upgrade with new transducers becomes significantly easier since the addition of further IB and/or AN does not require directly connecting the transducers to the data acquisition system with very long and expensive analog cables.

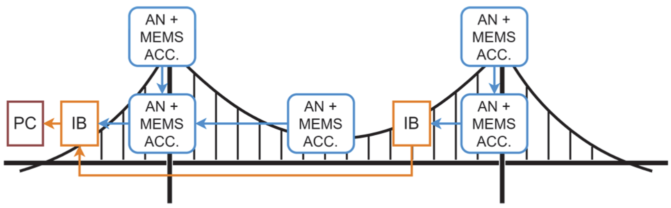

Fig. 12: Scheme of the proposed solution (orange wire: LAN connection over fiber, blue wire: digital A^2B subnet over UTP).

Another suitable employment for our system is the spot measurement in preliminary experimental tests, thanks to the easy and fast installation procedure. In [19], a flyover structure modal analysis has been performed by measuring accelerations from a bridge in BreBeMi highway, a strategic infrastructure connecting the cities of Brescia, Bergamo, and Milano (Italy). The measurements consisted of the data acquisition of 30 different accelerometers distributed among three spans with an overall length of 240 meters. In that case, the proposed system would have avoided the employment of several long and expensive cables, simplifying the installation and removal of the measurement set-up.

VI. Conclusion

A full-digital, low-cost health monitoring system for civil structures and infrastructures was proposed. The described solution is based on an Interface Board and a series of Acquisition Nodes, connected to the Interface Board in daisy-chain topology through a digital A^2B bus. Each acquisition node integrates a digital MEMS triaxial accelerometer. The design complexity and cost of the proposed system is minimal since data acquisition of digital MEMS accelerometers and data transmission are carried out by dedicated digital nodes. Hence, neither Analog-to-Digital (A/D) converters or programmable devices (e.g., microcontroller, DSP, or FPGA) are required. The complexity and cost of the cabling is minimized too, since the nodes communicate by means of UTP cables, thus avoiding bulky and expensive analog wiring between each piezo-electric accelerometer and the analog acquisition system.

A forced modal analysis experiment was performed on a truss, by employing an analog traditional system based on piezo-electric transducers connected in star topology, in parallel with the proposed digital solution. Frequency Response Functions between the Impact Hammer and the accelerometers were calculated and compared for the two systems, showing an excellent agreement. Then, a modal analysis was performed, demonstrating that the presented system provides identical results to the traditional system, particularly in the evaluation of mode shapes which are the modal parameters more sensitive to measurement synchronization.

Eventually, several application examples were provided, such as health monitoring of long bridges, high-rise structures or large buildings, and preliminary measurement campaigns with temporary systems. In these cases, the solution presented in this paper would provide a series of advantages with respect to traditional systems. Among these, ensuring data synchronization, which is mandatory for modal analysis, fast and easy installation, highly demanded for temporary measurements, and considerably reduction of cabling length, system complexity and cost of the system.

The authors are going to finalize the prototype in a commercial product, and real case studies will be described in subsequent papers.

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