3rd SEERC Conference Vienna 2021
Cooperation • Sustainability • Future

SEERC
South East European Regional Council

Paper no 1129

CIGRE South East European Regional Council Conference 2021 in Vienna, Austria

Innovation and New Technologies

A Wireless Monitoring System to Identify Wind Induced Vibrations in HV Transmission Lines

G. DIANA, D. TARSITANO, M. MAURI, F. CASTELLI DEZZA, F. ZANELLI, A. MANENTI, F. RIPAMONTI
Dipartimento di Meccanica - Politecnico di Milano
Italy
giorgio.diana@polimi.it

SUMMARY

Conductors of High Voltage Transmission Lines are affected by wind induced vibrations that can lead to fatigue failures of fittings and conductors themselves. Monitoring of these phenomena is very important in order to avoid the sudden break of an in-service line and to define the predictive maintenance of the system. Vibration recorders actually employed for field monitoring do not assure a suitable time window to cover all the different wind conditions, they allow to measure only the bending amplitude at the suspension clamp and do not offer any real time alert. For these reasons a new Wireless Monitoring System has been developed specifically for this context, taking advantage of new technologies such as wireless communication and energy harvesting that make possible to obtain compact devices, characterized by long autonomy and on board computations, able to measure the free loop vibration amplitude in the desired points of the instrumented span. In the paper, the hardware composing the wireless system is analysed and a deep insight of the algorithms developed for detection of Aeolian vibrations, Subspan Oscillations and Galloping is carried out. The system has been adopted for the first time in a real monitoring field test in Canada: this campaign has allowed to verify the correct functioning of the devices under extreme weather conditions and to obtain many data. It’s showed how this data have been processed in order to obtain useful information regarding the strains to which conductors are subject because of the wind action. In the end a comparison between experimental and numerical data, obtained by means of a suitable software, is carried out in order to validate the full procedure.

KEYWORDS

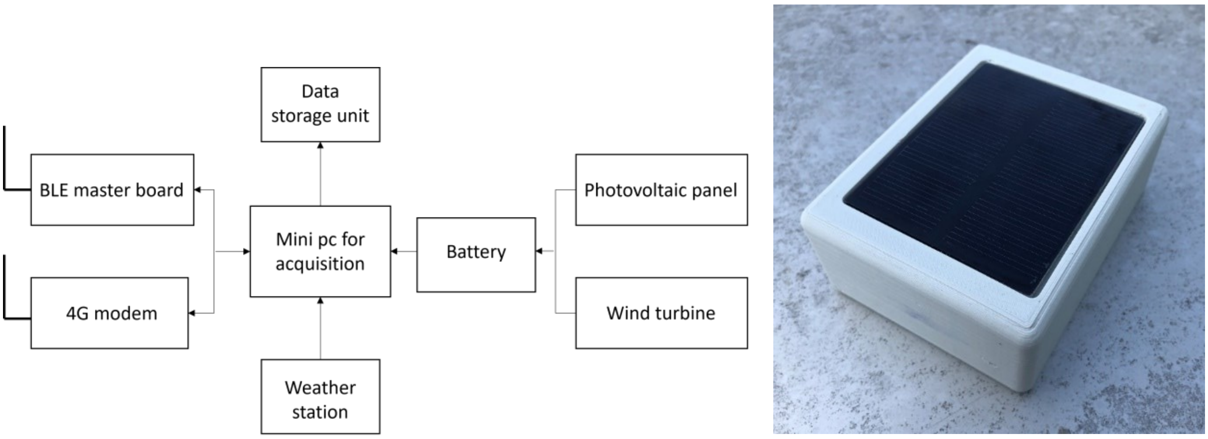
Cable Vibrations - Monitoring - Fatigue - Residual Life

Introduction

Wind induced vibrations on High Voltage Transmission Lines (HVTL) are a well-known issue which expresses itself in the form of Aeolian Vibrations, Subspan Oscillations and Galloping: all these three mechanisms can produce fatigue failures of fittings and conductors themselves [1]. Evaluation of fatigue parameters have been performed in past years by means of vibration test on laboratory span in order to better understand conductors and fittings behaviour with respect to fatigue issues [2]; however, field tests on operative transmission lines are preferred since they represent the real case scenario where also the real wind excitation is present. Fatigue indicators commonly used for conductors and fittings residual life estimation are Y_b, which is called "bending amplitude" and represents the amplitude of conductor relative to the clamp [3,4,5,6], and fy_{max}, which represents the product of antinode amplitude of vibration y_{max} by frequency f [7,8,9,10]. The bending amplitude Y_b is usually taken for expressing the severity of exposure to fatigue since it is related to the strain measured at the top surface of the conductor adjacent to the suspension clamp, which is a position quite accessible to measurement purposes: for this reason, it has been used for several years for vibration measurements of operating lines [11]. Nowadays, new technologies have been developed and this improvement has allowed the continuous antinode amplitude monitoring, through which it's possible to obtain the fy_{max} parameter [2]. From literature, it clearly comes out that measurements of Y_b in the vicinity of span extremities represent only a part of the vibration; in fact, in-span measurements are needed in order to perform an adequate vibration risk analysis since all span locations where conductor movement is restrained may be at risk. For these reasons fy_{max} can be considered a parameter much more representative than Y_b in terms of conductors and fittings fatigue state [2]. Actually, in the field of HVTL a real monitoring system useful in order to study lines behaviour with respect to wind induced motions is not available [12]. The monitoring state of the art in this field is still represented by vibration recorders that are used in specific cases, such as the effectiveness check of a damping system installed on new lines and the residual fatigue life estimation in the case of existing lines. Vibration recorders are quite heavy devices (their weight is around 5 kg) which have to be mounted at the suspension clamp, namely the sensor probe is placed at 89 mm away from the measuring point, in order to measure the bending amplitude Y_b; their installation on the specific span require a temporary outage of the line (in very rare cases they can be installed on the line still under tension) [13]. Since they are battery supplied, the monitoring time window is quite short (usually it can last about one month). The consequence of this constraint is that data coming from such a short monitoring period could not cover a good set of wind conditions and the related cable frequencies and therefore could not be sufficiently realistic to be used for a fatigue life estimation. In recent years, the research field in Structural Health Monitoring (SHM) has shifted away from traditional wired monitoring systems to smarter wireless sensors because these last ones offer several advantages: onboard computation, lower cost, less invasive installation, small size and performance comparable to wired devices [14]. In many fields, such as SHM for civil structures, wireless monitoring systems are already an established way to perform trusted measurements, therefore the main idea was to develop a system of this kind also for transmission line monitoring, where vibration recorders are still widely adopted. The wireless system can be used for two main purposes: the first is represented by a real time warning function, based on statistical tools, useful when extreme weather conditions occur (thunderstorms, snowstorms, etc.), while the second and main role of the system is to gather fatigue information about line components with the aim of performing predictive maintenance and avoiding fittings and conductors failures. This purpose can be reached if fy_{max} is measured in suitable points of the line and the level of the strain of the conductor can readily be defined with available software as ATTRA [1]. This new smart monitoring system is composed by a certain number of sensor nodes, which are able to communicate with the base station where the gateway, which includes a mini pc, a modem and a weather station, takes place. By means of this system, the fy_{max} parameter can be computed measuring the antinode amplitude displacement in any point of the span, with particular interest near the clamp of vibration dampers, air warning spheres and for bundles between spacers; moreover, it's possible to obtain real time data from the transmission line remotely from any location in the world. The paper is structured as follows: in Chapter 1 the hardware composing the system is analysed in detail while an overview of the software embedded both on the sensor nodes and on the gateway is carried out in Chapter 2. In the end, Chapter 3 is focused on the experimental campaign that has taken place in Manitoba (CA) on a 500 kV DC HVTL and that has allowed to assess for the first time the performances of the developed system in a real case monitoring under extreme weather conditions.

Chapter 1 – Hardware

The wireless monitoring systems developed for the vibration monitoring of conductors of HVTL is composed by a certain number of sensor nodes and a gateway. A block diagram which illustrates the devices composing the gateway is shown in Figure 1a. The sensor nodes are compact and light devices able to perform periodic accelerometric measurements: the core of the sensor is a custom board on which a MEMS triaxial accelerometer and a microcontroller used to perform data pre-processing on board are mounted. The communication module is represented by 2.4 GHz transceiver that allows the node to communicate wirelessly the acquired data through the Bluetooth Low Energy (BLE) protocol. In the end, on the board finds place an integrated circuit responsible of the on board power management. This last feature is very important for the global functioning of the sensor node since it is completely autonomous from the energetical point of view thanks to presence of a 500 mW solar panel. This energy harvester is able to recharge when needed a 2000 mAh Lithium Polymer (Li-Po) battery, which represents the main power supply of the device. For what concerns the enclosure, the board is placed inside a Chlorinated Polyethylene (CPE) 3D printed box, which offers a good resistance with respect to external actions (vibrations and impacts) and weather actions while keeping the device light and not acting as a shield for the antenna integrated on the board (Figure 1b).



(a) (b)

Figure 1- (a) Block diagram of the gateway, (b) External view of a wireless sensor node

The described nodes are able to communicate and to transmit acquired data to a master board which, together with the mini acquisition pc, represent the main components of the gateway part. The master board has the role to gather all data coming from the active sensor nodes which are then stored on the mini pc and transmitted remotely by modem through 4G connection. The main features of the mini pc are a very low power consumption (around 10 W) and the ability to automatically power on in case of an electrical outage. An essential device of the gateway is the weather station, since it allows to collect wind data in terms of wind speed, wind direction with respect to the line and turbulence intensity and some important environmental information such as temperature, humidity, dew point, etc. This kind of data will be directly correlated to vibration ones as it will be shown in the following. The whole gateway can be connected directly to a 220 V power supply when it is available on the monitoring area, otherwise it can be alimented by batteries which are recharged by means of energy harvester, as it is in the case of the Manitoba field test.

Chapter 2 – Software

The wireless monitoring system object of this paper has been endowed with software specifically developed for the purpose of conductors vibration monitoring. Overall, the software can be distinguished between the firmware installed on board on the sensor node and the acquisition software installed on the mini pc. On the sensor side, the on board firmware is itself divided between the microcontroller and the Bluetooth communication module with different purposes. The sensor node duty cycle is represented by a time period where the node is not working, called "sleep time", and the measurement time period; for the developed sensor node it has been chosen a 30 s wake time such that it wakes up every 30 seconds and go in sleep mode after having performed the measurement and transmission stages. This feature allows to have periodic measurements that, in the case of the specific application where wind represents a slowly variable phenomenon, can be seen truly as a continuous monitoring and in the same time it makes it possible to obtain a really long autonomy, enhanced by the use of solar energy harvesting. The whole process is managed by the on board firmware: during sleep time the microcontroller is put in a very low power mode while the communication module is in a reset one. After the wake on, the microcontroller acquires data from the accelerometer, namely 512 samples with a sampling frequency of 400 Hz in the standard mode, performs the Fast Fourier Transform (FFT) and transmits by means of the communication module synthetic data to the gateway. Data are then stored on the mini pc, where the acquisition software is present. A Matlab code has been developed with the purpose of driving the communication with sensor nodes, receiving data and saving it in a compact and easy way. The code has been created in order to manage properly the measurement of the different vibration phenomena (Aeolian Vibration, Subspan Oscillations and Galloping) affecting transmission lines, as it will be explained in the following. The acquisition process begins when nodes wake up and transmit this information to the mini pc through the gateway. When all nodes are awake, the pc sends a trigger to all the nodes to start an acquisition of the vibrations with the modality of Aeolian Vibrations (512 points with a 400 Hz sampling frequency), which represents the standard acquisition mode since Aeolian Vibrations is the most frequent kind of instability affecting transmission lines. At this point, the microcontroller of each node performs the FFT and transmits the FFT maximum amplitude and the related frequency to the pc. For each group of nodes, the pc defines the maximum amplitude detected as Max Amp and the related frequency fmax and it requests to all the nodes of the group to transmits the amplitudes corresponding to fmax and to the adjacent spectrum lines (lower and upper ones) of the FFT previously computed. Meanwhile, the pc receives from the weather station also wind data in terms of wind mean speed, wind direction with respect to the line and index of turbulence. Each of the problems related to the wind excitation occurs in different wind speed ranges, as can be appreciated in Figure 2.

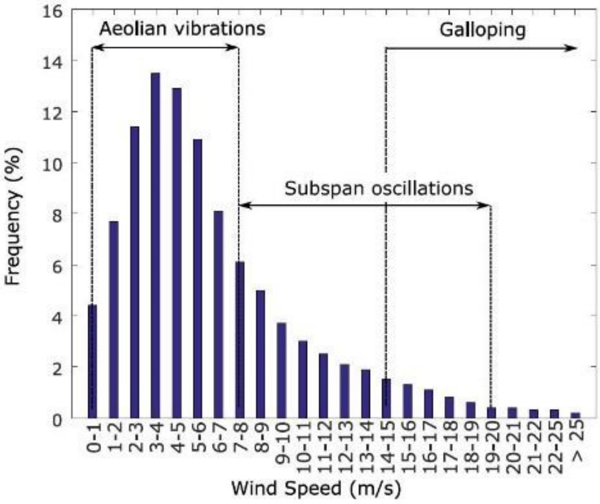


Figure 2 – Wind speed ranges for Aeolian Vibrations, Subspan Oscillations and Galloping

For this reason, when the wind speed measured from the weather station exceeds a fixed threshold (defined as 7 m/s), the pc automatically sends a trigger to the nodes to work at lower sampling frequency: a low pass filter is switched on in the nodes microcontroller and the FFT sampling frequency becomes 25 Hz. In this way, using the same procedure as before, vibrations in the form of Subspan Oscillations and Galloping can be detected. Sensor nodes remain in this modality until the wind speed value drops under the threshold, when they automatically return to the Aeolian Vibrations measurement mode. Finally, all data detected are stored on the computer and they are transmitted remotely by the modem through 4G connection. By means of another Matlab code, starting from the Max Amp and the related frequency fmax values, fatigue indicators fy_{max} for Aeolian Vibrations, the maximum relative amplitude for Subspan Oscillations and the maximum amplitude for Galloping are obtained and, by means of a suitable software, in all the points of the line strains are defined.

Chapter 3 – Manitoba Field Test

The wireless monitoring system described so far has been adopted for a monitoring campaign of wind induced vibrations on a High Voltage Transmission Line in Manitoba (Canada) in February 2019. This field test was needed to confirm the effectiveness of the conductors damping system and it has allowed to prove the ability of the wireless system to work properly in a real case scenario under quite extreme weather conditions. The line, as already mentioned, was the 500 kV DC OHTL Bipole III; the span subject to monitoring was 485 m long, equipped with 9 spacer dampers and characterized by a triple bundle configuration of the AAAC Φ38.01 mm conductor. A brief recap of conductor properties is reported in Table I.

Table I – Conductor properties of the Bipole III instrumented span

Conductor designation	Stranding	External Diameter [mm]	Mass [kg/m]	UTS [kN]
AAAC 806-A4-61	Al alloy: 61x4.22 mm	38.01	2.354	213.7

As described deeply in Chapter 1, the wireless monitoring system is essentially composed by sensor nodes and the gateway part. Since the monitoring location was far away from any source of power supply, it has been decided to take advantage of energy harvesting in order to recharge the batteries needed to run the system. The arrangement on the tower of the mini wind turbine and of the solar panel (representing the energy harvesting system), of the weather station and of the cabinet of the gateway is visible in Figure 3.

Figure 3 – Arrangement of the base station on the lattice structure of the tower

The choice of a hybrid system composed by the wind turbine and the solar panel has been motivated by the availability of few solar hours per day in February, therefore pairing the panel with a wind turbine able to carve out energy even for low wind speed (about 5 m/s) has seemed the best option. For what concerns sensor nodes, it has been decided to place some of them on the lower conductor and the other ones on the upper conductor in order to monitor Subspan Oscillations (Figure 4).

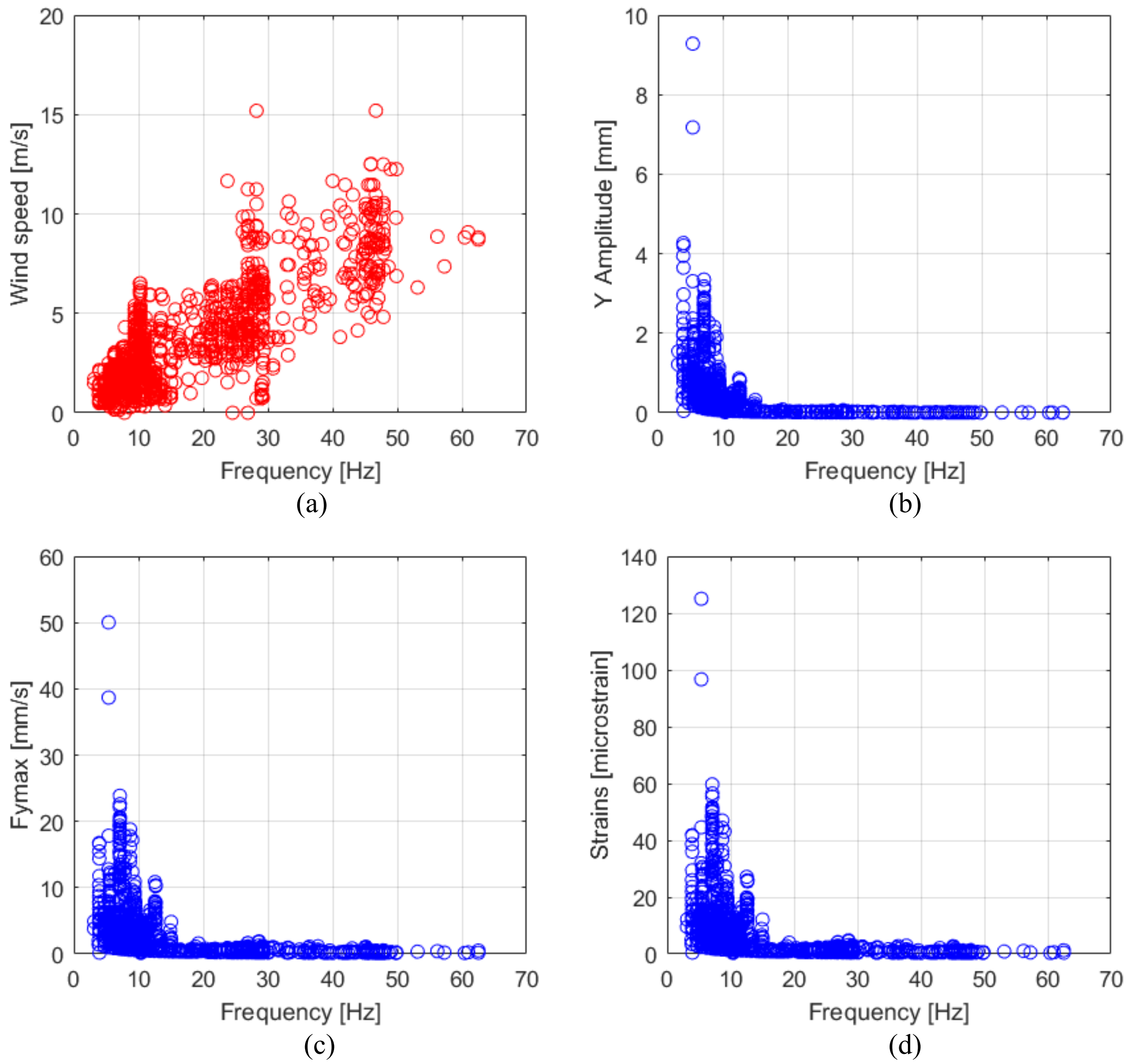
(a) (b)

Figure 4 – Sensor nodes positioning on the bundle : (a) on lower conductor, (b) on upper conductors

The clamping system for mounting sensors on the conductors has been designed specifically for this test and the installation has been fast and straightforward if compared to vibration recorders one: once decided the position where the sensors have to be mounted, the operation is performed simply by tightening two bolts. It has to be remarked that the wireless system has worked properly in difficult conditions, characterized by few solar hours and very low temperature (up to -25°) that have challenged the whole hardware; nevertheless, many useful data have been collected during a 3 months-time window and the main obtained results are here reported. Firstly, it's important to underline the possibility to have a direct correlation between vibration and wind data. In Figure 5a it's possible to observe a quasi linear relationship between the wind speed acting on the line and the vibration frequency of the conductor: frequencies between 4 and 60 Hz, typical of Aeolian Vibrations, are caused by wind speed between 1 and 10 m/s and they are related by the Strouhal formula:

$$f = 0.18 \frac{V}{D} \tag{1}$$

Where 0.18 is the Strouhal number for a circular section, V is the wind speed and D is the diameter of the cable.



(a)

(b)

(c)

(d)

Figure 5 : Experimental data plot of :(a) Wind speed versus Vibration Frequency, (b) Vibration Amplitude versus Vibration Frequency, (c) Fy_{max} versus Vibration Frequency, (d) Strains versus Vibration Frequency.

In addition, from this figure it can be noted that a big quantity of data is related to low frequency vibrations, namely below 15 Hz. Vibration amplitude of conductor in terms of displacement is represented in Figure 5b: it's clearly visible that higher amplitudes are reached for low frequencies, while in the frequency range of Subspan Oscillations (1÷1.5 Hz) no significant values have been collected.

Data are represented in terms of fy_{max} parameter in Figure 5c while in Figure 5d strains are computed with reference to 3.11 of EPRI Orange Book [11] as:

$$\varepsilon = cost \ \cdot fy_{max} \tag{2}$$

Where the constant for this type of conductor is assumed to be cost = 2.5.

In the end, it's interesting to have a look at the 3D graph of Figure 6 where it can be appreciated the possibility given by this system to correlate directly vibration amplitude data with wind ones (direction with values around 0° and ±180° indicates a perfectly orthogonal wind with respect to the line; viceversa values around ±90° represent a wind flowing parallel to the line).

It can be noticed that the highest vibration amplitude values are reached for wind speed up to 2 m/s and for wind direction of about 40-50° and -130°, which are values representing wind flows with an important transversal component with respect to the line.

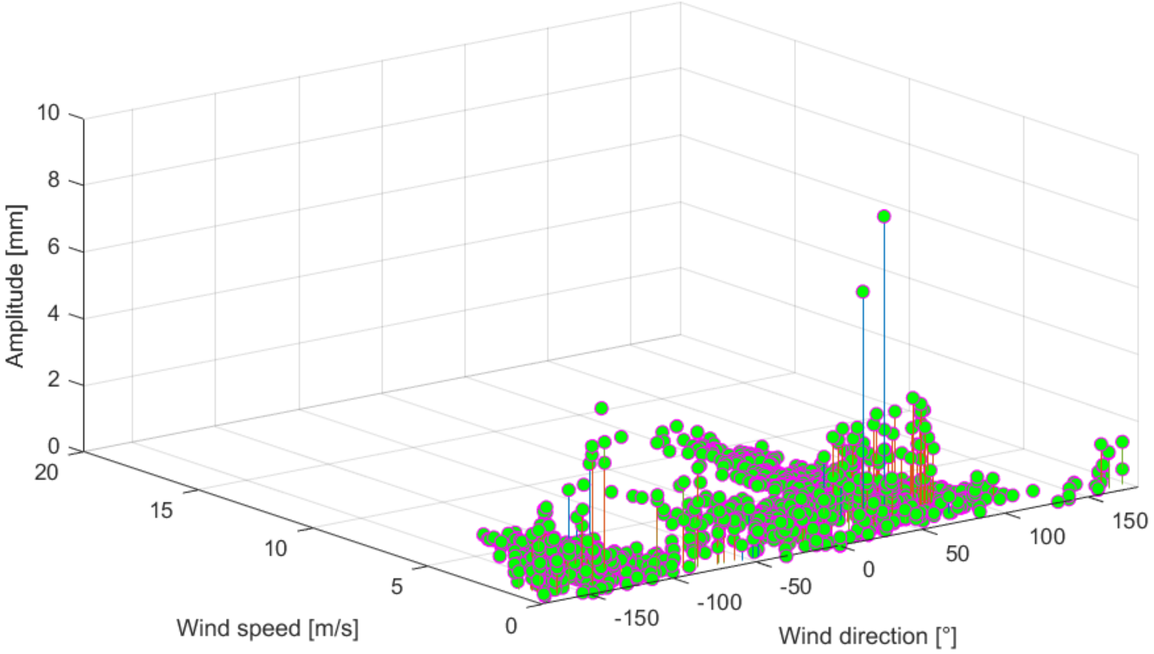
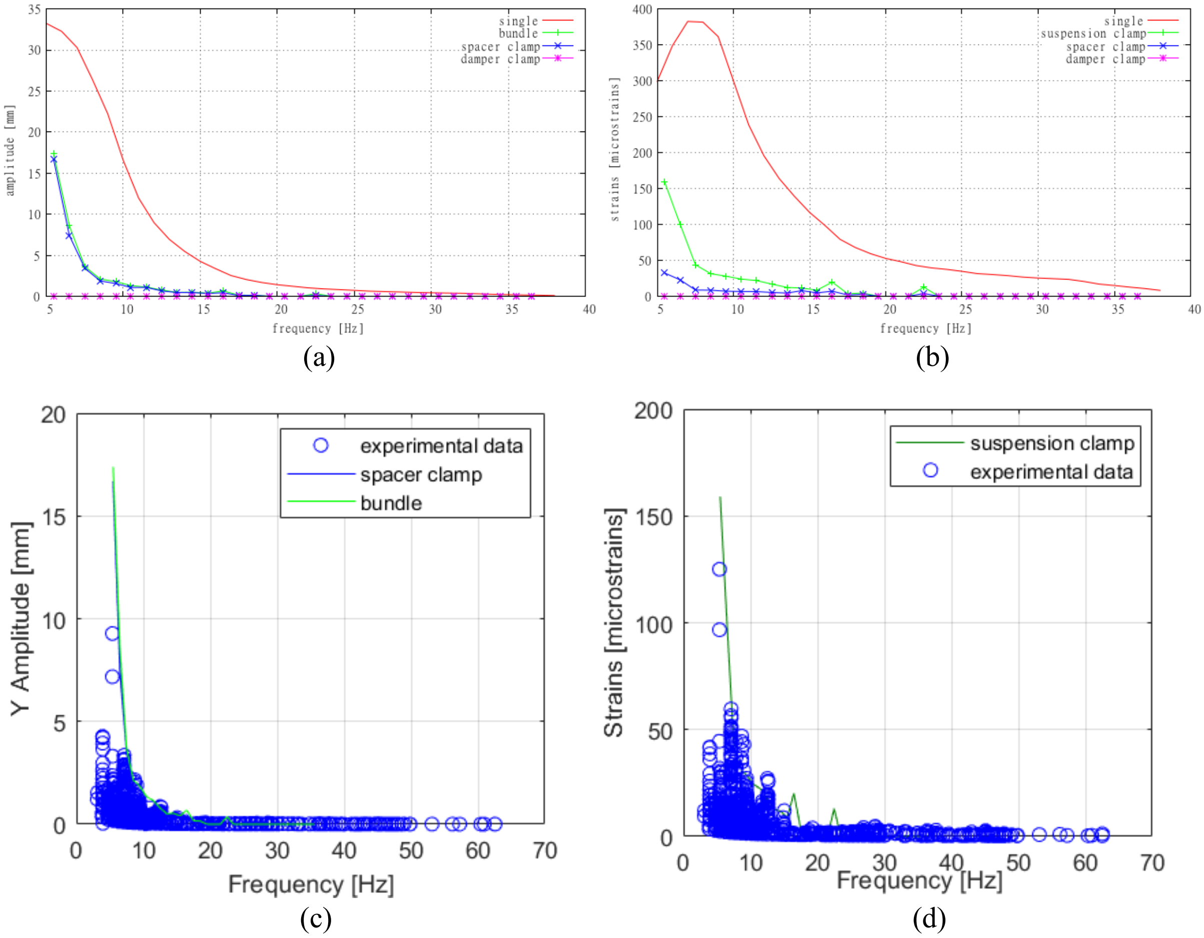


Figure 6 - Correlation between Vibration Amplitude and Wind speed and Wind direction

Some numerical computations have also been performed in this context by means of the ATTRA software developed in the Department of Mechanical Engineering of Politecnico di Milano: in Figures 7a and 7b analytical data of amplitude and strains have been plotted for the single conductor case (red curve), the bundle one (green curve) and for spacer (blue curve) and damper clamps (violet curve), with this last case characterized by null values since no dampers were present on the instrumented span.
In the end, experimental data and analytical results have been compared in order to validate the measurement set-up. As can be seen in Figures 7c and 7d, the trend of experimental data collected during the monitoring field test in Manitoba well reproduces the analytical curves both in terms of vibration amplitudes and strains, assessing the overall measurement performances of the developed system.



(a) (b)

(c) (d)

Figure 7 – Analytical results computed through ATTRA software in terms of : (a) Amplitude, (b) Strains ; Comparison between analytical and experimental results in terms of : (c) Amplitude, (d) Strains.

Conclusions

A new Smart Wireless Monitoring system has been developed in order to monitor the effect in terms of strains produced on transmission line conductors by wind induced vibrations. The hardware and software sides have been analysed in detail, focusing on the sensor nodes innovative features. A field campaign in Canada has allowed to test the system in a real case scenario and by means of a comparison between the experimental data collected and numerical results computed by software the overall measurement performances of the developed system has been assessed.

BIBLIOGRAPHY

[1] G. Diana et al., “Modelling of Vibrations of Overhead Line Conductors – Assessment of the Technology”. (Springer Green Books – Technical Brochures – ISBN 978-3-319-72808-7-February 27, 2018).

[2] S. Guérard, P. Van Dyke, J. L. Lilien, “Evaluation of power line cable fatigue parameters based on measurements on a laboratory cable test span”. (Eighth international symposium on Cable Dynamics, ISDC 2009, 125-135).

[3] G. B. Tebo, “Measurement and Control of Conductor Vibration”. (AIEE Transactions, vol. 60, 1188-93, 1941).

[4] IEEE Committee Report, “Standardization of Conductor Vibration Measurements”. (IEEE Transactions on Power Apparatus & Systems, Vol. Pas-85, No. 1, 10-20, 1966)

[5] Z. Josiki, A. Kierski, K. Lewichi, W. Lieszkowski, “New Overhead Transmission Lines in the Polish Network-Service Experience”. (CIGRE Report 22-05, 1976)

[6] L. Cloutier, C. Dalpè, A. Cardou, C. Hardy, S. Goudreau, “Studies of Conductor Vibration Fatigue Tests, Flexural Stiffness and Fretting Behaviour”. (Third Intl Symp. on Cable Dynamics, Trondheim, 197-202, 1999)

[7] J. C. Little, D. G. MacMillan, J. V. Majercak, “Vibration and Fatigue Life of Steel Strand”. (AIEE Transactions, vol. 69, 1473-9, 1950).

[8] Alcoa, “Overhead Conductor Vibration”. (Aluminum Company of America, 1961).

[9] B. Hondalus, “Comparative Vibration Fatigue Tests-84/19 ACSR ‘Chukar’ vs 61-strand 5005”. (IEEE Transactions Paper, Vol. Pas-83, 971-4, 1964).

[10] C. W.Smollinger, R. B. Siter, “Influence of Compressive Forces on the Fatigue Performance of Bethalume Strand Wire”. (IEEE Conference Paper C65 237, 1965).

[11] EPRI Transmission Line Reference Book: Wind-Induced Conductor Motion. (EPRI, Palo Alto, CA:2006.1012317).

[12] IEEE, 2006, IEEE Guide for Aeolian Vibration Field Measurement of Overhead Conductors. (IEEE Std 1368 TM-2006).

[13] Y. Hu, K. Liu, “Inspection and Monitoring Technologies of Transmission Lines with Remote Sensing”. (Academic Press, 2017).

[14] L. Zhu, Y. Fu, R. Chow, B. F. Spencer Jr., J. W. Park, K. Mechitov, “Development of a High-Sensitivity Wireless Accelerometer for Structural Health Monitoring”. (Sensors, 2018)