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DEVELOPMENT OF MEASURING DEVICE FOR STORING AND VIBRATION IN ELECTRIC CABLES

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Abstract. *This work presents consists of the design, fabrication and testing of a prototype vibrometer whose function is to acquire and store vibration data cables for transmission lines of electricity. These data are essential for the study of fatigue resistance in the cables, allowing the designer to estimate the useful life of a given transmission line.The vibrometer is developed based on a micro-plate which manages a controlled displacement sensor, an A / D converter, an RS232 port and a recorder SDcard. This vibrometer operates similarly to commercial equipment, but stores the data in the time domain, preserving numerous temporal information, which differentiates it from commercial equipment.The mechanical design of the vibrometer contemplates the realization of direct measurement methods and inverse, typical for this type of test.The results obtained by the vibrometer were excellent when compared to results obtained in the reference laboratory.*

Keywords: *Wind Vibration, Vibration measurement, Data storage vibrations*

1. INTRODUCTION

The present work is the development of a prototype sensor and mechanical vibration data acquisition module with application in the area of fatigue of electricity conductor cables. This prototype will collect laboratory data, in order to better understand the measurement techniques as a part of development of a module for field application.

The primary function of the assembly is designed to provide the amplitude signal of the cable bending at a standard point versus time. Bending is defined as the relative displacement of the driver in relation to the suspension clamp at a distance 89 mm from the last contact point between cable and suspension clamp IEEE (2006). The data obtained in the field are used for operation and maintenance engineers to estimate the locations most susceptible to fatigue failure of the cables and to set the appropriate intervals for inspection. Project area for these field data will provide subsidies for future transmission line projects with greater reliability and lower cost. The collector equipment such information is called vibrometer.

Typically the measurement methods used by these appliances can be classified in the following ways:

- Method bending amplitude technique based on the relationship proposed by Poffenberg-Swart (1965). This work is called the direct measurement method.
- Method reverse bending amplitude is a technique based on the relationship proposed by Hardy and Brunelle Cloutier (1991). This work is called the reverse measurement method.

There are two types of commercial vibrometers currently used: The Pavica (manufactured by ROCTEST GROUP) which uses the method of reverse measurement and Vibrec (manufactured by PFSTERER) which uses the direct measurement method. These two devices can’t provide data on temporal sequence, mainly due to limitations of their memory. In the developed prototype is possible to know the order of the data, by using flash memory micro SD.

We conducted in this study the design, manufacture and test of the prototype vibrometer intended for laboratory. This is the first stage of a research and development which has as final proposal to build a vibrometer for field application.

1.1 Introduction to the mechanical issue

The incidence of wind in transmission lines of electricity causes mechanical vibrations in power cables, which may lead to fatigue failure of the cables, this cyclical phenomenon will cause future cracks in some of the strands of the cable, which can lead to transmission failure. The worst blackout due to mechanical fatigue caused by wind vibration occurred in 2001. That blackout left 11 states of Brazil without electricity due to the disruption of a conductor of a transmission line located in the southeastern region. The event caused the shutdown of 13 of the 18 turbines of Itaipu, responsible for 30% of the energy supply of the federation, resulting in damage estimated at $ 100 million, as well as those immeasurable losses of life and injury to the country's image on the world stage (FADEL, 2010).

Fatigue in power cables is accompanied by a phenomenon of great importance called Fretting, coming from the friction caused by slippage of the wire conductor cable between themselves and in relation to the suspension clamp fittings, generating wear (starting material inside the clip) filaments in the cable, as a rule, failures occur in the region of fretting.

To analyze the evolution of this mechanical problem is important to correlate data on the dynamic behavior of the system, such as: Vibration frequency, amplitude shift of the cable, measured in standard position 89 mm from the last point of contact between the cable and clamp suspension, and also number of cycles sustained in different frequency

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bands and displacements. The displacement amplitude values are then converted into voltage values (σ) by the equation Poffenberger-Swart (1965). The stress values (σ) served as the basis for calculating the remaining lifetime of the cable. The vibrometer acts providing data to perform these calculations.

1.2 Objetives

This job has a technological nature and your goal is the development, manufacturing and testing of a prototype vibrometer to conduct measurements in fatigue endurance tests of cable conductors of electricity. The mechanical design of the sensor should contemplate the use of the same in the two measurement methods, forward and reverse. This equipment must provide data in the form of amplitudes displacement histogram and frequencies, in other words, provide the user with the order of loads suffered by the system, using the micro SD flash memory for storage of data. The proposal is to develop a portable and easy installation and affordability. As already mentioned the future goal is to manufacture a device for field work and as a direct result of this work we intend to file a patent.

2. METHODOLOGY

In this step we will present the following topics: Mechanical Design, Instrumentation Blade and Electronic Design

2.1 Mechanical Design

The main criteria evaluated for the mechanical design of the sensor were: Evaluation of vibrometer format, since their physical form has some influence on the mechanical system, fixing the sensor to the cable, in order to make your installation an easy task, as future projects will be made on-site testing, the materials and manufacturing processes used in order to lower the cost and also the mass of the sensor has little influence to the system.

It is important to remember that one of the goals of this production was to develop two bases for fixing the prototype system: one to perform a measurement on the model of Poffenberg-Swart (1965). called amplitude method of bending, simply known as direct measurement, and another measurement following model HARDY, Cloutier e Brunelle (1991) called range reverse bending, or simply reverse measuring.

The displacement sensor used was a load cell composed of a steel blade instrumented with strain gauges connected in a full Wheatstone bridge.

The description below provides illustrative pictures and cover information relating to mechanical shape and materials used in the manufacture of the device.

2.1.1 Shape and Form Base Clamp Sensor Direct Measurement:

Figure 2.1 is an illustration of the format of the vibration sensor for direct measurement, as well as its form of fixing the suspension clamp. To better visualize the form of mounting the sensor to the suspension clamp illustration is 180o rotation with respect to the physical system.

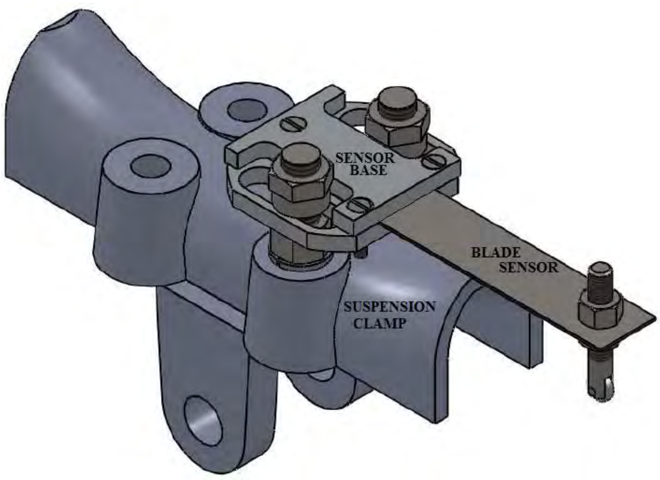

Figure 2.1 - Format and method of attachment of the base vibrometer for the direct measurement of the cable suspension clamp.

This constructive form was defined by the team aiming the following characteristics: Fast and easy installation of the device to the system, easy installation of the instrumented blade-based sensor, the simple and low cost manufacturing process.

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2.1.2 Shape and Form Base Clamp Sensor Measurement Inverse:

Figure 2.2 below represents the format of the reverse sensor for measuring.

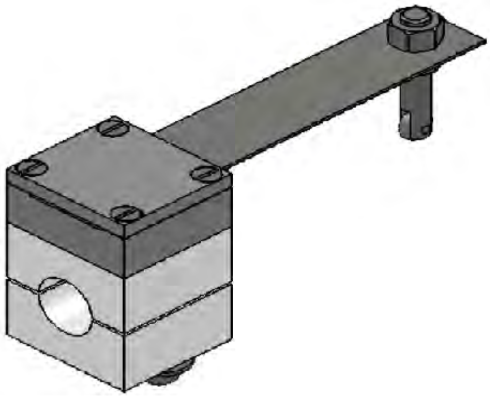


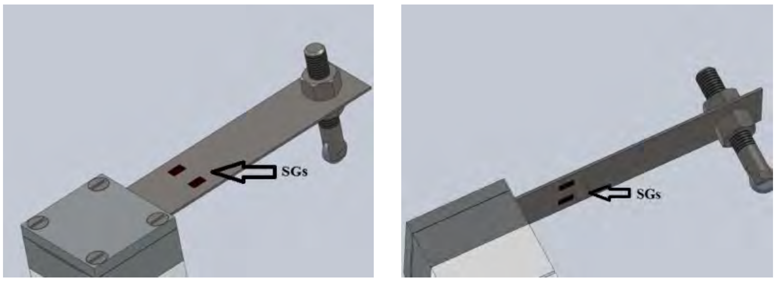
Figure 2.2 - Isometric view of the prototype for reverse measurement

The instrumented blade is stainless steel and its mounting at the base of the sensor is done by a lid and a lower base both made of aluminum, the choice of the aluminum was due to the material having relatively low mass and simple machining process. Bases in coupling the sensor to the cable IBIS, 397.5 MCM14 material used was tecnil, differentiating the outer material of the cable where it is attached, which is aluminum, in order to prevent surface wear on the cable due to the greater flexibility with respect tecnil for aluminum, and have the aforementioned same advantages as the aluminum.

2.2 Instrumentation Steel Blade:

The four strain gauges (SGs) were bonded near the bezel, in a region of relatively high blade deformation lengthwise. The convention of the upper and lower blade was aiming that the output signal proportional to the deflection is always positive, thus suitable for data collection system.

Figure 2.3 illustrates the positioning of SGs on the top side (a) and bottom (b) of the blade.



(a) (b)

Figure 2.3 - Positioning of SGs in the faces of the blade. (a) Top view. (b) Lower panel.

The SGs the top and bottom side are equidistant with respect to the crimping blade. It is considered that the two SGs glued on the upper side of the blade are R1 and R3 and R2 and R4 underside. Figure 2.4 represents the arrangement of SGs present in the blade connected in a Wheatstone bridge (DOEBELIN, 1990).

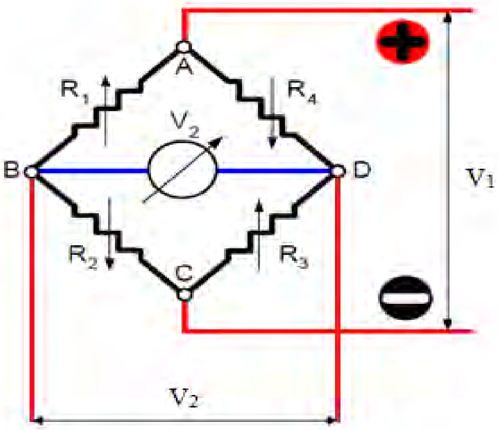


Figure 2.4: Arrangement of the blade strain gauges on Wheatstone bridge circuit.

This arrangement makes it possible to compensate the difference between the coefficients of thermal expansion, strain gauge and instrumented piece. Figure 2.5 shows the electrical circuit connecting the strain gauges and the DB09 connector that connects the sensor to the vibrometer board.

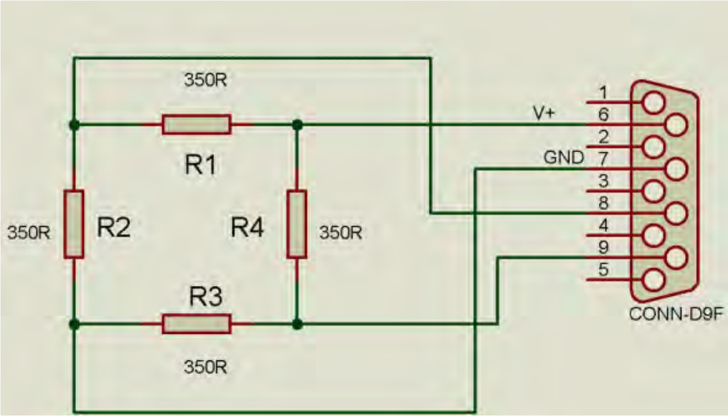


Figure 2.5 - Load cell circuit.

The Wheatstone bridge is powered through the pins 6 (V +) and 7 (GND). The pins 8 and 9 contains the bridge output voltage.

2.3 Electronic Design

The electronic design of the equipment sought to focus largely on the following:

- Large storage capacity of signals in the time domain, held in nonvolatile memory, SD-card;
- Frequency of data acquisition of up 200Hz;
- Auto-zero to facilitate the installation of displacement sensor in the system;
- Signal Amplifier with gain selectable for different applications;
- RS232 to view the collection of data in real time and also for future implementations of technology related to this type of communication.

At this stage we present the electronic technologies employed in the construction of acquisition module, which allowed reaching the desired characteristics.

2.3.1 The microcontroller

The vibrometer main circuit is a microcontroller that once properly programmed should be able to manage peripherals such as analogue to digital converter, display, indicators, RS232 communication system and external memory. The microcontroller chosen for the initial prototype was produced by Microchip PIC18F452 Technology Inc due to the following characteristics:

- Development platform relatively well known, RAM 1536 bytes;
- 256 bytes EEPROM, 16-bit architecture, programmable in C language;
- Internal A / D Converter 10-bit;
- Native SPI communication bus that allows communication with external devices such as memory and others;
- Native internal USART allows automatic management of communication with external devices with RS232 or RS485 protocol.

2.3.2 The compiler

To the family of PIC microcontrollers there are several commercial compilers in C language such as CCS, MPLabC, MikroC, WIZ C, HI-TECH C and other less known. There are still some compilers experimental free access, but extremely limited, such as JAL.

The choice of compiler is no easy task, since each has nonstandard and different functions. The compiler that was the most promising for the development of vibrometer was MikroC that compared the others, not the easiest to use but it brings implemented a set of tools for communication with the SPI bus, which will be connected to external memory SDcard.

2.3.3 Main Board of the Vibrometer

The main circuit board of the vibrometer houses the microcontroller and additional components such as capacitors, resistors and piezoelectric crystal oscillator. Figure 2.6 shows the physical construction of grouped main board to the circuit power supply and driver memory SDcard, in addition to connectors for connecting peripherals: LCD display, RS232 communication, signal amplifier and battery connector and external power supply.

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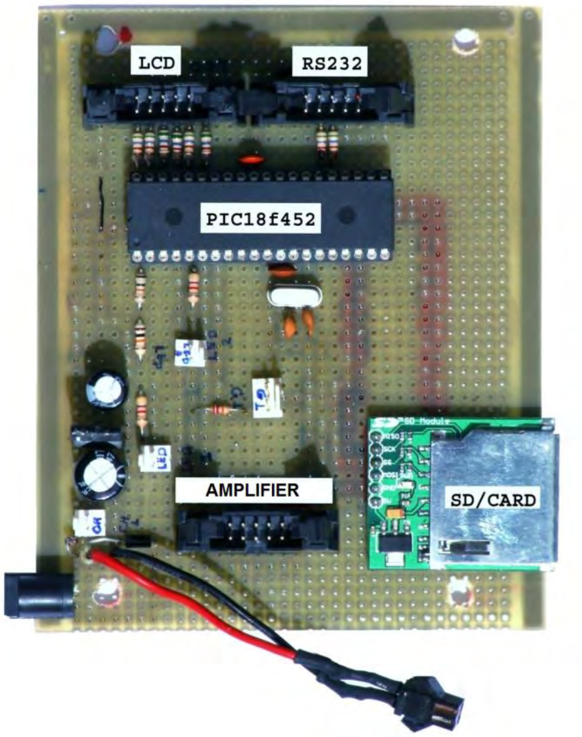

Figure 2.6 Construction of physical main board of the vibrometer

2.3.4 The firmware

Firmware is the software that is written to the microcontroller. It is responsible for the operation and control of the central and peripheral logic.

2.3.5 The Analog to Digital Converter

The PIC18F452 has 8 inputs, AN0 to AN7 devices that are configured as A/D port with 10-bit resolution operating in simple mode or differential, the default TTL voltage range, ie 0-5 volts maximum.

Converting 10 bits: 0b1111111111 to the decimal number system corresponding to the number 1024, or 0-1024 has 1025 discrete voltage levels. In this case the resolution of the converter is 5 V/1025 or 4.8 mV.

2.3.6 Signal Amplifier

The INA122 chip developed by Texas Instruments Inc, is the differential an instrumentation amplifier with low noise and high gain, powered with only positive voltage. This integrated circuit allows the adjustment of the gain by changing a single external resistor.

The level of voltage provided by the displacement sensor is in the range of millivolts. It is necessary then a circuit for the amplification of this signal to the range of volts. Considering the particular case of this application, it is intended to pre-load displacement sensor to near the center of the measurement range and therefore we will have the displacement variation around that point of time when the operation of the equipment. In this case the output voltage of the Wheatstone bridge differential voltage is always positive.

The physical construction of the circuit board with signal conditioner developed is shown in Figure 2.7, where it is possible to identify the DB9 connector which feeds and receives the signal from the Wheatstone bridge sensor displacement as well as the resistors Trimmers gain adjustment, adjusted for gain 600 and gain 1000, selectable by key CH2 whose drive is positioned in console module acquisition.

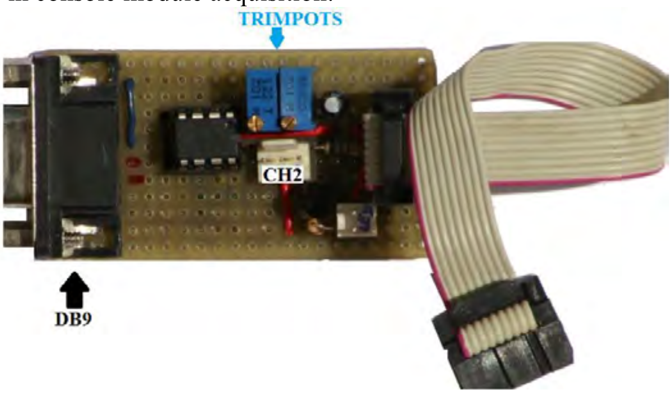

Figure 2.7: Operational Amplifier Board.

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2.3.7 LCD 16x2

The LCD display of 2 lines and 16 columns was built into vibrometer intended to ease the task of installing it in the clip, as he informs the position of the pre-loading of the sensor, in the measurement range of the A / D converter. Figure 4.19 shows the circuit connection LCD.

2.3.8 The RS232 communication board

A serial communication circuit RS232 standard was incorporated into vibrometer to allow data to be monitored in real time by a microcomputer. This communication is important in lab environments as well as in the testing phase of development of the vibrometer prototype.

Using RS232 is also important future implementations of technology related to this type of communication, for example, Bluetooth communication. Figure 2.8 shows its physical board.

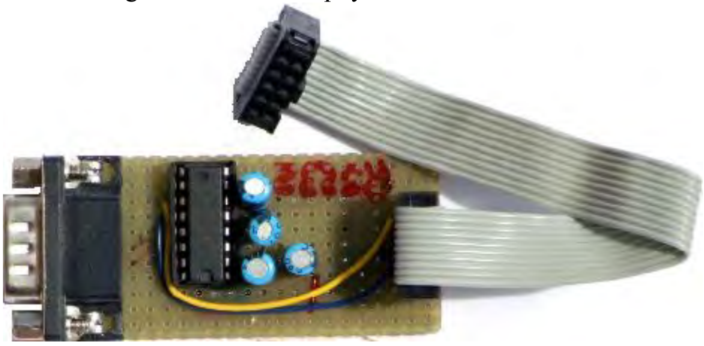

Figure 2.8 - RS232 communication board.

2.3.9 The vibrometer construction

The visual aspect of the construction of the prototype, the current version of vibrometer is shown in Figure 2.9.

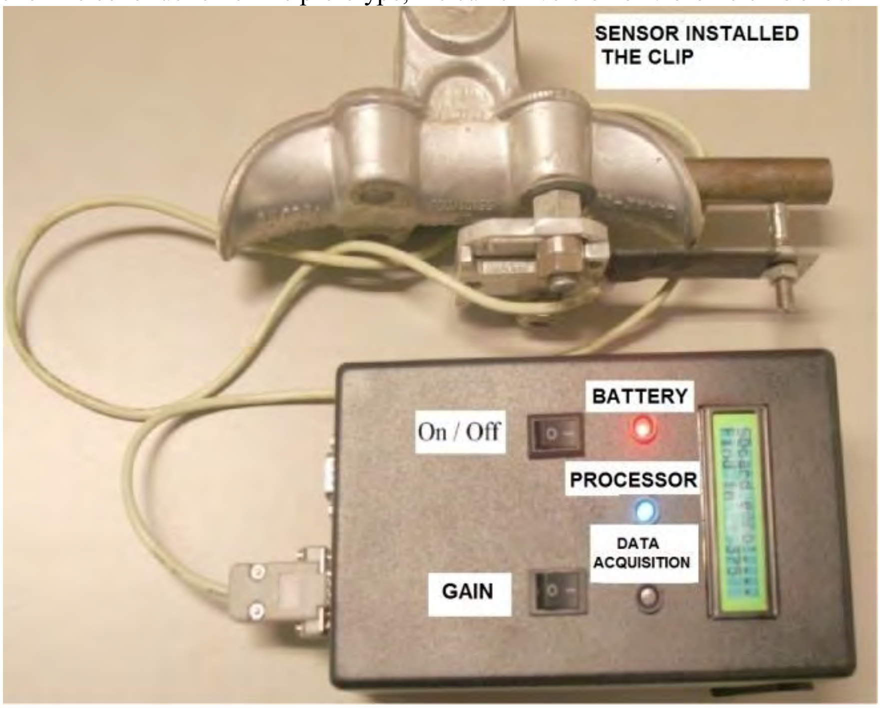

Figure 2.9 - Current vibrometer prototype, external view.

Figure 2.10 shows the inside of the mounting box, where you can see the bottom battery compartment and the motherboard. At the top of the figure shows the signal conditioning board, RS232 communication board and LCD display.

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Figure 2.10 - Current vibrometer prototype, inside view.

3. EXPERIMENTAL PROGRAM

In this module has been divided into two parts: Description of the Test Bench Cable Conductors and Data gathering.

3.1 Description of the Test Bench Cable Conductors

Figure 2.11 shows the schematic drawing of the test bench. The porthole have a total length of 46.8 m, and can be subdivided into two sub- portholes: The active porthole defines the length of the cable, and the passive porthole, only use for cable fixing.

The four blocks shown in Figure 2.11 are of concrete, to ensure the rigidity of the assembly. A sample of the cable is disposed on the two supports, which function as two articulation points: the suspension clamp and block 3 pulley. It is then fixed at the ends via clamps for anchoring load application.

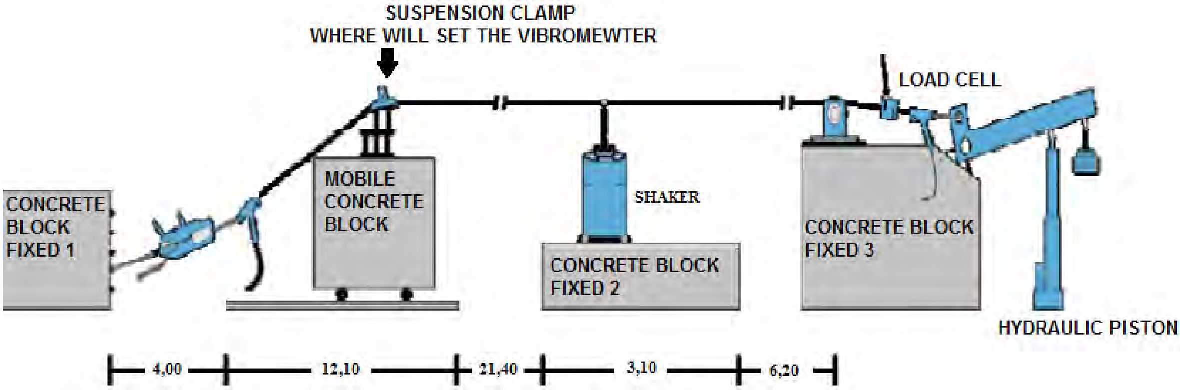

Figure 2.11 - Schematic drawing of the assembly test bench (modified - Fadel, 2010)

3.2 Data gathering

We performed a battery of tests for measuring both direct and reverse measurement.

The point used to control the displacement of the test is located in the vicinity of the cable suspension clamp, 89 mm apart to of the last point of contact between the base of the suspension clamp and cable, calling it "point 89". The edge of the mono articulated suspension clamp mounted on the bench, is located 68.5 mm from the reference point. Porting the distance between the last point of contact with the base of the cable clamp and the edge of the clamp is 20.5 mm.

Figure 2:12 shows the probe directly, properly installed in the system to perform the measurement of displacement Yb. It is important to remember that the roller sensor should be positioned centrally on the surface of the cable.

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Figure 2.12 - Measuring sensor directly installed on the system.

Figure 2.13 shows indirect measurement sensor installed in the system, along with the other sensors, accelerometer sensor and laser displacement, part of the lab instrumentation.

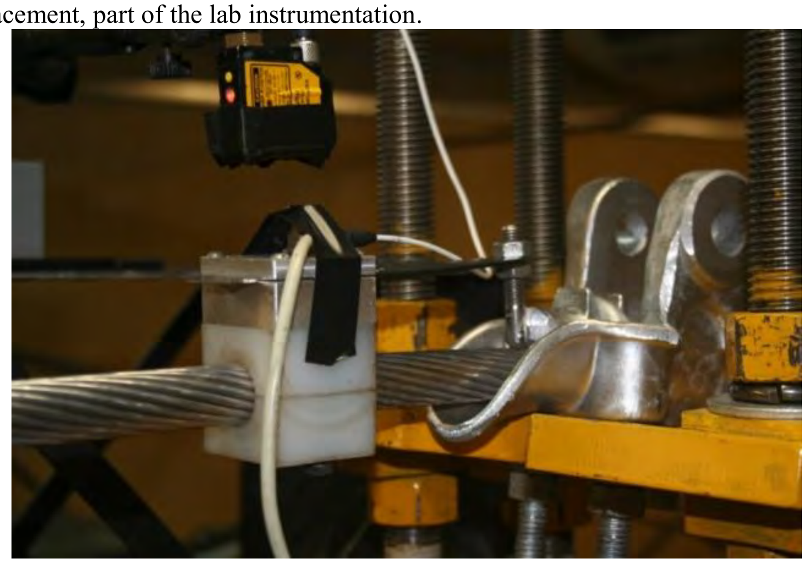
Figure 2.13 - Sensor Measuring System Installed in reverse.

4. RESULTS AND CONCLUSIONS

These module has been divided into three parts: Validation of measures undertaken by vibrometer, Results and Conclusions Direct Measurement (DM) and Reverse measurement results

4.1 Validation of measures undertaken by vibrometer

In accordance with the displacement inserted into the sensor an electrical voltage proportional will be generated. In order to obtain this curve (displacement / strain) was performed using a calibration standard instrumentation blades of different thicknesses and precision of 0.001 mm.

As the vibrometer can be adjusted to two voltage gains two different calibrations were made. For each measurement was made an average of 512 readings.

Figure 4.1 shows the calibration curve for gain 600 times the input value and the equation of fitting obtained, in the same way that Figure 4.2 shows the gain of 1000 times. It can be seen that the two gain adjustment is very close to 1, indicating a very linear response of the sensor.

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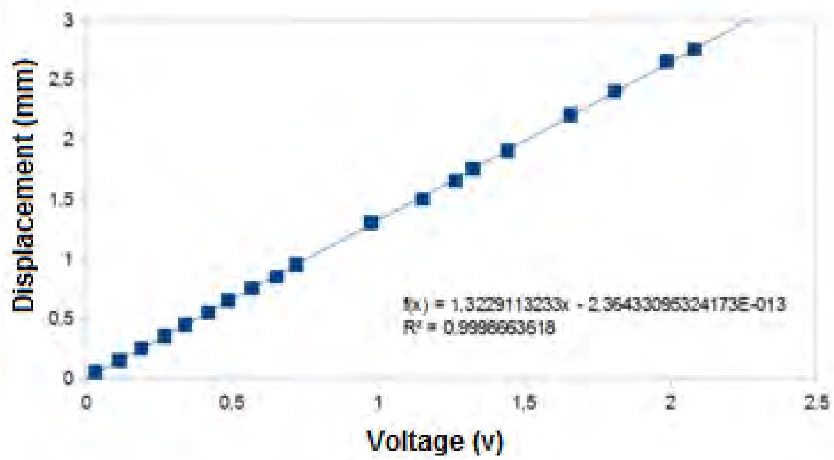

Figure 4.1 - Calibration curve for gain 600.

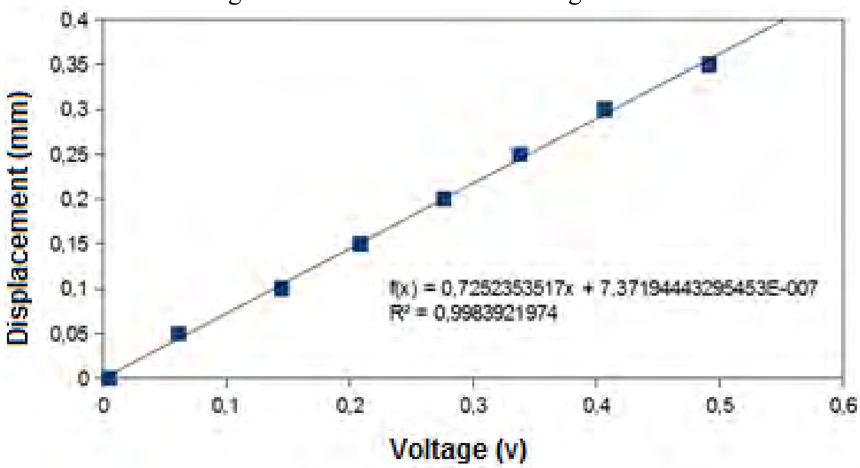

Figure 4.2 - Calibration curve for gain 1000.

The equations for the calibration have been implemented in the firmware so that the values stored in SDcard memory reflect the displacement in millimeters.

A standard practice in instrumentation is to use a standard measure at least 10 times more accurate than the instrument being calibrated. Considering the high degree of linearity of the sensor, the accuracy of the blades used [0.001mm] and the A / D converter 10 bit [1/1025], it can be stated that the accuracy of measurement vibrometer is at least 0.01mm, thereby validating the offset values collected by the sensor.

4.2 Results and Conclusions Direct Measurement (DM)

Table 4.1 shows the frequency values provided by the laboratory using the accelerometer which is the reference of the control software of the bench, frequency values measured at vibrometer and also the percentage of the vibrometer error in relation to the reference value.

Table 4.1 - Comparison between the values of frequency reference of the lab and frequency values measured at vibrometer in configuration of direct measurement.

Sample	Frequency (reference) [Hz]	Frequency (vibrometer) [Hz]	Freq. Error [%]
26	12,37	12,00	2,99
74-75	20,61	20,25	1,75
79-80	42,31	42,38	0,17
84-86	56,19	56,25	0,11
90-93	68,45	68,63	0,26
97-98	73,35	73,50	0,20

It can be observed that the frequency values measured at vibrometer in several samples in direct measurement configuration are compatible with the reference values of the lab.

Table 4.2 and Figure 4.3 show the comparison of the displacement Yb between Vibrometer in setting direct measurement and the laboratory reference, which is given by an accelerometer.

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Table 4.2 - Comparison between the displacement values between Yb Vibrometer in configuration of direct measurement and laboratory reference.

Sample	Frequency (reference) [Hz]	Displacement peak to peak Vibrometer [mm]	Displacement reference [mm]	Error [%]
26-27	12,37	1,544	1,500	2,94
74-75	20,61	0,837	0,800	4,64
79-80	42,31	0,992	0,900	10,24
84-86	56,19	0,582	0,600	2,96
90-93	68,45	0,388	0,400	2,88
97-98	73,35	0,320	0,300	6,67

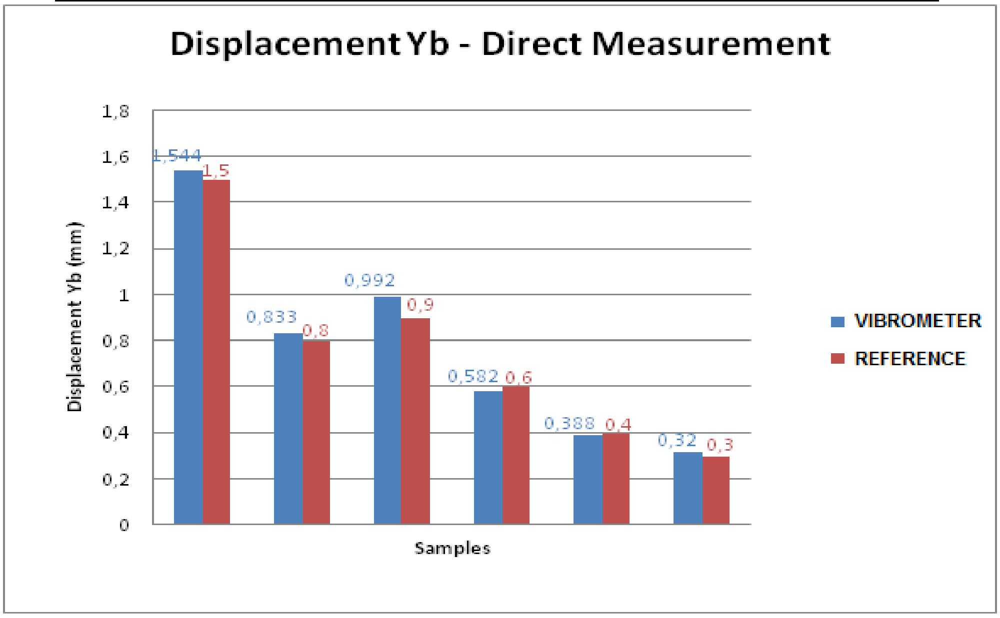

Figure 4.3 - Graphical representation of comparative Yb offset values between Vibrometer in direct measurement setting and laboratory reference.

Initial Considerations:

The laser sensor is more precise than the accelerometer sensor for measurement of displacement, since the accelerometer accumulates more errors due to double integration process of of the acceleration signal. The vibrometer directly measures the displacement through its instrumented blade. The accelerometer is attached to the cable. The vibrometer is fixed to the end of the U-bolt type clamp.

Direct Measurement Conclusion:

It is observed that with the increased frequency error also increases. This is an indication that there is relative movement between the screw and the U-type suspension clamp body, which is accentuated with increasing frequency, introducing an error component in the measurement of vibrometer.

4.3 Reverse measurement results

Table 4.3 presents the following values: Values of reference frequency provided by the laboratory, frequency values measured at vibrometer in the reverse measurement setup and values of the percentage error vibrometer relative to reference value.

Table 4.3 Comparison between the values of laboratory frequency reference and frequency values measured at vibrometer in reverse measurement setup.

Sample	Frequency (reference) [Hz]	Frequency (vibrometer) [Hz]	Freq. Error [%]
64-69	12,200	12,300	0,820
56-58	20,430	20,250	0,881
43-45	42,110	42,100	0,024
38-40	55,920	55,500	0,751
29-32	68,200	67,880	0,469
20-22	73,350	73,500	0,204

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It can be observed that the frequency values measured at vibrometer in several samples in reverse measurement configuration are compatible with the reference values of the lab.

Table 4.4 - Comparison between the displacement values between Yb Vibrometer in configuration of reverse measurement and laboratory reference.

Sample	Frequency (reference) [Hz]	Displacement peak to peak Vibrometer [mm]	Displacement reference [mm]	Error [%]
64-69	12,200	1,218	1,500	18,81
56-58	20,430	0,833	1,100	24,27
43-45	42,110	0,798	0,900	11,37
38-40	55,920	0,645	0,600	7,47
29-32	68,200	0,457	0,400	14,14
20-22	73,350	0,359	0,300	19,60

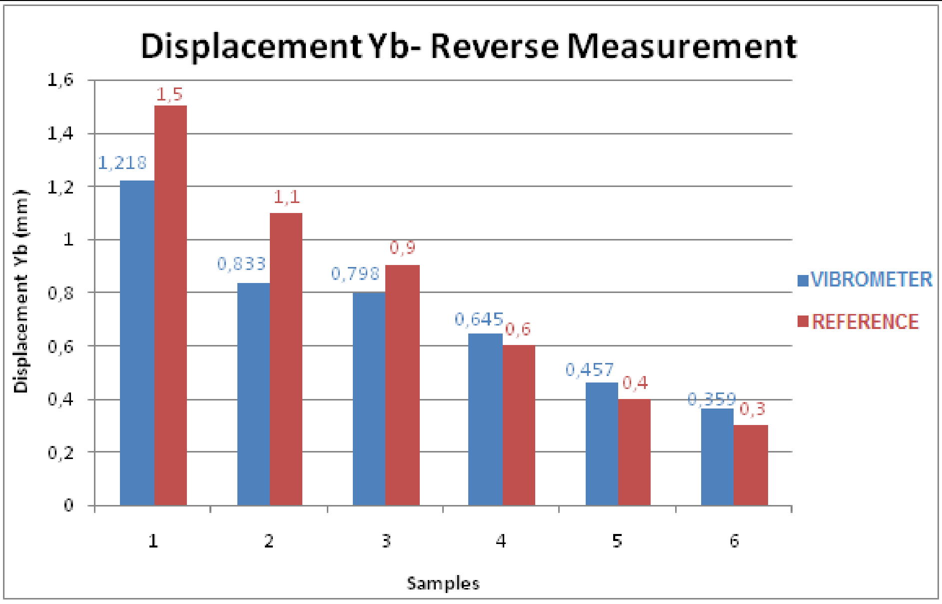

Figure 4.4 - Graphical representation of comparative offset values Yb between Vibrometer in reverse measurement setup and the laboratory reference.

In the process of reverse measurement the vibrometer is mounted on the handle, point 89. When the cable is in the uniaxial oscillatory motion, the cable cross section at this point is rotated. This fact promotes the addition of errors such that the blade instrumented flexing of vibrometer suffers a small unloading, which induces vibrometer to indicate measures displacement smaller than indicated by the accelerometer.

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