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Low-cost acoustic strain gauge assembly

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Abstract: The development of measurement systems in university laboratories allows reducing dependence on expensive equipment and creating customized solutions. The assembly of a low-cost acoustic strain gauge capable of measuring deformations with the order of microstrains is presented. The strain gauge was calibrated with a displacement gauge and neutralizing the interference of temperature variations. The results show excellent agreement with the presented theory, showing a linear relationship between deformation and the variable F (Hz^2) and a coefficient of determination r^2=0.998. Thus, it consolidates an initial basis in the development of a low-cost strain gauge, easy to assemble and with high precision.

Keywords: strain gauge, acoustic, strain measurement.

1. INTRODUCTION

The development of measurement systems within university laboratories allows reducing dependence on expensive equipment, to create customized solutions and, possibly, the emergence of innovative solutions. This article presents the initial phase of the development of a low-cost acoustic strain gauge (also known as vibrating wire strain gauge), this phase aims to validate and consolidate the theoretical basis through a first calibration.

The vibrating wire first appeared in the literature in the Dawidenkow (1928) publication. Upfold (1963) explains that such strain gauge is basically composed of a steel wire pre-tensioned between two supports fixed to the body to be examined, so a change in the dimensions of this body generates a variation in the tension of the wire that, consequently, causes a variation of the fundamental frequency thereof. This variation can be related to the value of the deformation through physical-mathematical models. The main advantages of this type of strain gauge are ease of attachment, robustness, precision and the ability to make measurements on materials with cracks, an important characteristic for experimental concrete tests.

The major disadvantage of the vibrating wire is its sensitivity to temperature changes, which can impair its accuracy. This problem will be circumvented in this paper with the use of a control gauge, which is mounted on an unloaded sample of the same material as the test specimen.

2. THEORETICAL BASIS

The fundamental frequency (f) of a wire in vibration varies with the square root of its tension (T), according to (1):

$$f = (1/2L)\times\left(\sqrt{T/m}\right) \qquad (1)$$

where L is the length and m the mass per unit length of the wire (Batten, Powrie, Boorman, Yu and Leiper, 1999).

Neild (2001) presents (2) for a tensioned wire between two supports fixed in a concrete specimen:

$$\varepsilon_s = G(f_1^2 - f_0^2) \quad (2)$$

where ε_s is the deformation of the specimen and f_0 and f_1 are the fundamental frequencies of the wire before and after the specimen is loaded, respectively. The constant G, gauge factor of the vibrating wire gauge, is defined by (3):

$$G = (l_w \varepsilon_0)/(l_s f_0^2) \quad (3)$$

where l_w is the length of the tensionless wire, ε_0 is the initial deformation relative to the fundamental frequency f_0 and l_s is the distance between the centers of the supports fixed to the specimen and to which the wire is attached.

By analyzing (3), it can be concluded that G is independent of the tension to which the wire is subjected in the pre-tensioning, and that when the same wire is used and the supports are fixed with the same distance between them, G will be the same. These conclusions are of fundamental importance since they indicate that when the calibration of the proposed assembly is done once, its reproducibility is possible without the necessity of new calibrations.

3. MATERIALS AND METHODS

3.1. Materials

The following materials were used to assemble each strain gauge: two M8x50 mm bolts drilled close to the base, a 2 mm bolt, four nuts, six washers, a guitar pickup, a small bracket to fix the pickup to one of the support bolts, Araldite glue and NP010 guitar string. Figure 1 illustrates the abovementioned materials in the strain gauge assembly.

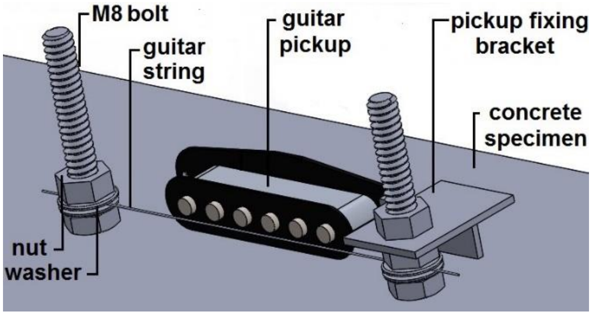

Figure 1. Assembly scheme (SolidWorks).

All of the materials shown in figure 1, with the exception of only the two M8 bolts, can be reused countless times in subsequent assays.

3.2. Assembly of the acoustic strain gauge

The assembly shown in figure 1 basically consists of the fixing of the two M8 bolts on the test piece and the passage of the wire in the bolts holes. However, two important details need to be met: pre-tensioning the wire and using the small piece of steel to keep the guitar pickup fixed to one of the supports, preventing any changes in the pickup position causing interference in the result of measurements.

The solution chosen in the present work to avoid the interference of a temperature variation in the measurements is to use a control strain gauge attached to a specimen that, unlike the other, will not be charged and will only be influenced by the temperature variation. With the values of the fundamental frequencies of the strain gauge fixed in the control specimen before ($f_{c,0}$) and after ($f_{c,1}$) of the loading, the equation (4) presented by Neild (2001) to replace the equation (2) is used, being ε_s^{load} the deformation caused by the loading, without influence of the temperature variation.

$$\varepsilon_s^{load} = G\left(f_1^2 - f_0^2 - f_{c,1}^2 + f_{c,0}^2\right) \quad (4)$$

A jig has been made to guarantee the same distance between the bolts in future measurements, so if the same guitar string is used, the gauge factor G will be the same.

3.3. Calibration

For the calibration of the acoustic strain gauge, an axial compression test was performed on a concrete specimen. The experiment is schematically illustrated by figures 2 and 3.

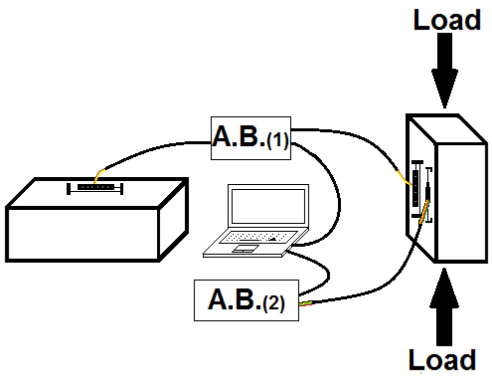

Figure 2. Schematic drawing of the test.

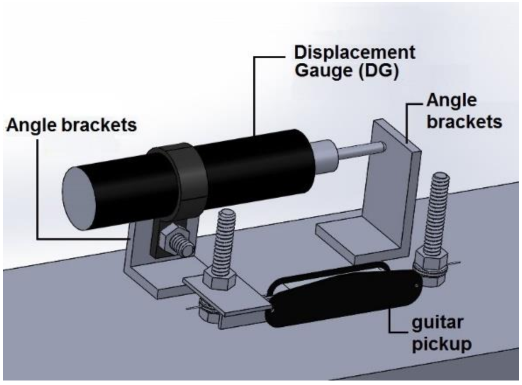

Figure 3. More detailed illustration of the use of angle brackets to fix the DG.

As shown schematically in figure 2 the guitar pickups of the two concrete specimens are connected to the NI 9234 acquisition board (A.B.(1) in figure 2), which in turn is connected to the notebook. A script developed in *MatLab* receives the signal and performs its processing, calculating the response in the frequency domain. There is also the acquisition board (A.B. (2) in figure 2) that receives the signal from the displacement gauge (DG) through a ¼ Wheatstone bridge connection.

After the experiment was set up, its execution follows these steps: **1.** Fundamental frequencies of the two vibrating wires, the control one and the other in the specimen that will be loaded (two specimens of 10x10x20 cm were used) were obtained before any type of loading imposition. **2.** A load of 50000 N was applied to one of the specimens by the press PC 200 (EMIC), and the new fundamental frequencies were measured in the two acoustic strain gauges, in addition to noting the displacement given by the displacement gauge (DG); **3.** A load of 50000 N was added to that applied in step three, and again the new fundamental frequencies and the displacement of the DG were measured; **4.** The process is repeated until a value of 250000 N of loading is reached, keeping the experiment within the elastic behavior of the concrete; **5.** With the data collected equation (4) is transformed into (5), being the variable F defined by (6):

$$\varepsilon_S^{load} = GF \quad (5)$$

$$F = \left(f_1^2 - f_0^2 - f_{c,1}^2 + f_{c,0}^2\right) \quad (6)$$

For the signals from the pickups, a five second period of acquisition was used, with a sampling rate of 4 kHz. From these signals the first 1.5 second was cut, as the period near the excitation has higher amplitudes which generally take away processing precision.

4. RESULTS

With the values of the fundamental frequencies of each of the two strain gauges for each load value, together with the values measured by the displacement gauge, table 1 was set up.

Table 1. Experiment results.

		Fundamental Frequency (Hz)	
Load (kN)	DG (μstrain)	Loaded gauge	Control gauge
0,0	0	1000,00	1101,55
49,8	25	921,85	1101,55
100,7	41	843,75	1101,55
148,5	65	757,81	1101,55
197,6	86	664,10	1101,55
247,2	109	546,87	1101,55

Each frequency value of table 1 is the average of five measurements, but it is worth mentioning that rarely all five values were not all equal. It can be noted that the values for the fundamental frequency of the control vibrating wire remained the same, indicating that during the experiment there was no variation in temperature large enough to cause changes in measurements.

Using equations (5) and (6) table 2 was set up with the values of F for the respective deformations.

Table 2. Calculated F and ε obtained by the DG.

ε (μstrain)	F (Hz²)
0	0,00
25	150192,58
41	288085,94
65	425724,00
86	558971,19
109	700933,20

With the data of table 2, the gauge factor G was found through a linear regression of the points plotted on a graph (figure 4).

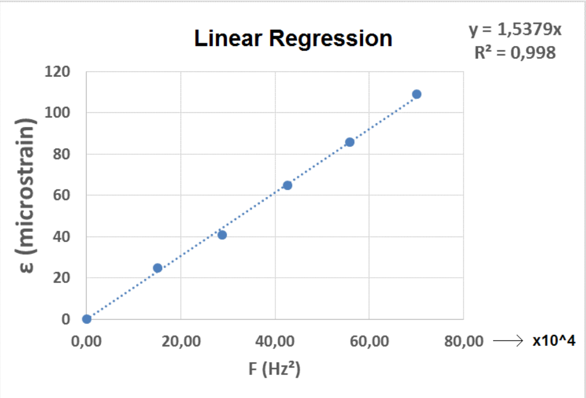

Figure 4. Linear regression using table 2 data.

Figure 4 shows that the value of the coefficient of determination r^2 was 0.998. What also demonstrates the excellent quality of the model is the residual values (difference between predicted and experimental values), which remained lower than 3.5 microstrains. The equation of the trend line found was $\varepsilon = (1.5379E\text{-}4)\ F$, that is, $G = 1.5379E\text{-}4\ s^2$.

5. CONCLUSIONS

It was presented in this paper a low-cost acoustic strain gauge, easy to assemble, with accessible parts, able to measure small deformations with good precision and of easy reproducibility. The assembly presented can serve as an inexpensive and accurate alternative to electrical strain gauges.

This was the initial phase of the development of a low-cost acoustic strain gauge, and the objective of validating and consolidating the theoretical basis was achieved. In the next phases, it is intended to make the assembly more systematized, to investigate the probability of using cheap microcontrollers for the acquisition of data and to migrate the data processing to free software. The calibration test presented was sufficient for the purpose of the present study, but for the subsequent studies, it can be refined.

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