Concept Development of a Vibration Sensor for Industrial Boilers

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Abstract

An acoustic horn has been developed for Sasol Synfuels in Secunda. It has been concluded that this is the best methodology for dislodging ash agglomeration on the boiler tubes, since it can perform this act while boilers are in operation, thereby eliminating the need to shut down boilers for cleaning. The acoustic horn utilises sound energy that induces vibration and strain on the boiler substructure components. This results in a concern to develop vibration and strain sensors in order to measure these phenomena. An accelerometer is considered to monitor vibration signals, while a secondary strain-gauge sensor is considered to measure strain signals. The analysis entails a predetermined assessment of the suitable sensor parameters for the anticipated input signals. The appropriate accelerometer for this kind of application is concluded to be a piezoelectric accelerometer with a sensitivity of 1000 mV/G as most suitable. Furthermore, a strain-gauge sensor of a quarter-bridge type one with a gauge factor of 2 and nominal resistance of 350 Ω is deemed to be most suitable.

Keywords

Vibration, Strain, Sensitivity, Nominal resistance, Gauge-factor.

1. Introduction

Development justifications are established with intentions to address the problem statement. Which is to develop sensors that will be capable of monitoring vibration and strain signals. The methodology adopted comprises of a design approach that considers different types of sensors, all weighed at specified criterion for development suitability. Furthermore, various logics are demonstrated on how final selections for development are concluded.

2. Concept Development

2.1. Development Justification

A none-intrusive cleaning method for boiler tubes at Sasol Synfuels power station at Secunda, in the Mpumalanga province is preferred over conventional methods that require boiler shutdown (Shandu and Kallon, 2021). On grounds that the conventional methods interfere with the plant's productivity. The elected none-intrusive cleaning method utilizes sound energy waves, produced by an acoustic horn (also known as sonic horn). Due to the nature of sound propagation and the effectiveness required, there is a requisite to control and operate the sonic horn. If the acoustic horn's sound frequency is too low, it will produce higher sound energy waves that will resonate with the plant's harmonious frequency and cause damage to plant components.

Conversely, if the sonic horn's sound frequency is too high, excessive dB levels may be reached and annoy plant personnel, while also not being effective in removing slag agglomeration on the boiler tube surfaces. To prevent these undesirable outcomes posed by adopting the acoustic horn, there needs to be a regulatory system incorporated into the configuration. The regulatory system comprises of sensors and a control system (Mhlongo and Kallon, 2021). Sensors detect various physical parameters processed to provide signal feedback to the user(s). The control system drives the acoustic horn's sound frequency as intended through a set point by the user(s).

Integrating this hypothesized regulatory system into the acoustic horn configuration creates a controlled environment as intended by the user. The potential damage is eliminated while achieving optimum cleaning of the boiler tubes.

2.2. Sensor Development Concepts

2.2.1. Accelerometer Sensor

Accelerometers are versatile with a variety of sizes, range, and designs. It is therefore a requisite to appreciate the signal characteristics intended to be measured. Furthermore, environmental constraints are accounted for in order to select a suitable accelerometer sensor.

2.2.2. Hypothesized environment

Sasol Synfuels power station imposes various conditions for the equipment in use. The expected conditions include excessive humidity due to steam generated (Shandu et al, 2019). The probable vibration signals induced on the boiler tubes as a result of the acoustic horn sound energy will be of high amplitude and frequency. Table 1 shows a deduced criterion in selecting the applicable accelerometer developed.

Table 1. Accelerometer Selection Criterion.

Type	Accelerometer		
	MEMS capacitive	Piezoresistive	Piezoelectric
Accuracy	Low	High	High
High vibration amplitude measuring capability	No	Yes	Yes
High vibration frequency measuring capability	No	Yes	Yes
Excessive humidity exposure proof	No	Yes	Yes
Measured signal to voltage output	No (capacitance)	No (resistance)	Yes (voltage)
Vibration measurement	Yes	Low sensitivity, ideal for shock measurement, less useful for vibration	Yes

2.2.3. Observation

Three (3) accelerometer types are taken into consideration for a high-level assessment. The micro-electromechanical system (MEMS) capacitive accelerometer has low accuracy, unable to measure high vibration amplitudes and frequency signals. It cannot be utilized under excessive humid conditions, and outputs a change in capacitance as a measurement. The piezoresistive and piezoelectric accelerometers show similar characteristics, with the following exceptions; the piezoresistive accelerometer is ideal for shock measurements, while the piezoelectric accelerometer is ideal for vibration measurements. Another exception is the measured output domain; a change in resistance in the case of a piezoresistive accelerometer, and a voltage measurement in the piezoelectric accelerometer.

2.2.4. Final selection

Considering the powerhouse conditions and Table 1 requirements, the elected accelerometer developed for this application is a piezoelectric accelerometer. The final selection is based on the grounds that the piezoelectric accelerometer meets all the stipulated criteria. The decision is further motivated by the fact that piezoelectric accelerometers are usually the first choice for vibration measurements. This is due to factors such as great sensitivity, resolution, easy installation methods, and having a wide continuum frequency response.

2.2.5. Fundamental further development

In order to design this type of accelerometer, there is a requisite to estimate the appropriate sensor's sensitivity. Considering a random force input that will induce an assumed vibration level of 0.1 g as the maximum value. Sensitivity can be determined as follows;

$$Vibration\ signal\ (g) \times sensitivity\ (mV/g) = mV\ or\ V \tag{1}$$

Case I

If the accelerometer sensitivity is 10 mV/g;

$$0.1 \times 10 = 1\ mV \tag{2}$$

Final answer translates to 0.001V, this suggests that the signal will clip the sensor, therefore higher sensitivity is desirable.

Case II

If the accelerometer sensitivity is 100 mV/g;

$$0.1 \times 100 = 10\ mV \tag{3}$$

Final answer translates to 0.01V, this suggests that there is reduced signal distortion, however, the 100 mV/g sensitivity is still not adequate to provide a cleaner signal. Therefore, higher sensitivity is still desirable.

Case III

If the accelerometer sensitivity is 1000 mV/g;

$$0.1 \times 1000 = 100\ mV \tag{4}$$

Final answer translates to 0.1V, this suggests that a sensor of 1000 mV/G will be suitable for this kind of application, as there is no signal distortion or clipping. Furthermore, this sensitivity value will provide a cleaner signal (higher signal to noise ratio).

2.2.6. Chosen accelerometer properties

Figure 1 illustrates the chosen piezoelectric accelerometer which has the capability of measuring high vibration amplitude and frequency at high accuracy levels. It is also humidity exposure proof and outputs the measured signals in the form of voltage.

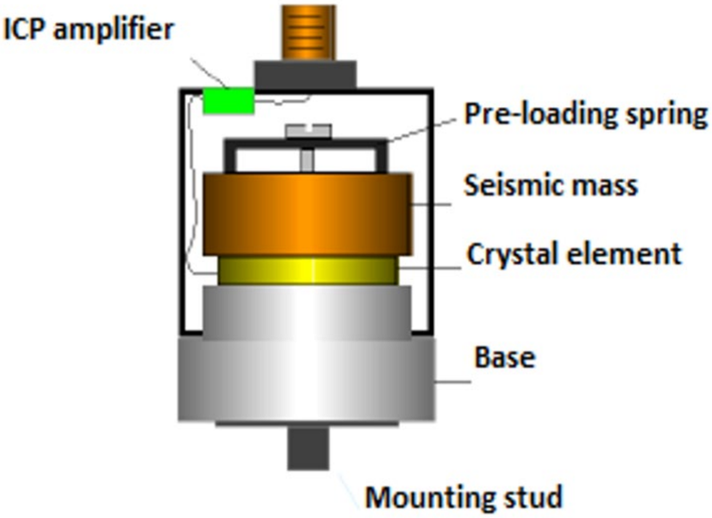

Figure 1. Typical ICP Accelerometer (Ghemari et al., 2018).

2.3 Strain-gauge Sensor

For the same strain gauge, changing the bridge configuration can improve its sensitivity to strain. For example, the full-bridge type I configuration is four times more sensitive than the quarter-bridge type I configuration. However, full-bridge type I requires three more strain gages than quarter-bridge type I. It also requires access to both sides of the gaged structure. Additionally, full-bridge strain gages are significantly more expensive than half-bridge and quarter-bridge gages (National Instruments Corp, 2020). For a summary of the various types of strain-gauge bridge configurations, as shown in Table 2.

2.3.1 Final selection

The anticipated type of strain to be measured on the boiler tubes as a result of sound energy is bending strain. This is due to the deduced logic that the acoustic horn sound waves will be perpendicular to the target surface (boiler tubes). As a result, a quarter-bridge type I is considered to be the suitable configuration in order to measure bending strain.

2.3.2 Fundamental further development

In order to design this type of strain-gauge, there is a requisite to estimate the appropriate sensor's parameters, namely, resistance (Ω) and the gauge factor.

The most common nominal resistance values of strain-gauges are 120 Ω, 350 Ω, and 1,000 Ω. Typically, a higher nominal resistance is preferable on the basis of self-heat reduction capability. As a result, a resistance of 350 Ω was considered since it is an average value out of the three (3) common nominal resistances.

Another common practice in the industry is that a gauge factor of 2 is normally considered for strain-gauges. As a result, a gauge factor of 2 was considered for development.

Table 2. Strain-Gauge Bridge Configuration Types (National Instruments Corp, 2020).

Measurement Type	**Quarter -bridge**		**Half-bridge**		**Full-bridge**		
	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2	Type 3
Axial strain	Yes	Yes	Yes	No	No	No	Yes
Bending Strain	Yes	Yes	Yes	Yes	Yes	Yes	No
Compensation							
Transverse Sensitivity	No	No	Yes	No	No	Yes	Yes

Temperature	No	Yes	Yes	Yes	Yes	Yes	Yes
Sensitivity							
Sensitivity (@1000 με)	~0.5 mV/V	~0.5 mV/V	~0.65 mV/V	~1.0 mV/V	~2.0 mV/V	~1.3 mV/V	~1.3 mV/V
Installation							
Number of Fused Gauges	1	1*	2	2	4	4	4
Installation Location	Single Plane	Single Plane	Single Plane	Contrary Side	Contrary Side	Contrary Side	Contrary Side
Number of Wires	2 / 3	3	3	3	4	4	4
Bridge Completion Resistors	3	2	2	2	0	0	0

*A secondary strain-gauge is mounted but not bonded with the material in concern

2.3.3 Chosen strain-gauge properties

Figure 2 illustrates the chosen strain-gauge circuit configuration. The quarter-bridge type 1 has three bridge completion resistors and one strain gauge. This chosen configuration achieves a sensitivity of 1000 με at 0.5 mV/V. Due to the three bridge completion resistors, there is a single fused gauge into the configuration, thereby utilizing less excitation energy. Ultimately, axial and bending strains can be measured through this chosen quarter bride type one strain-gauge.

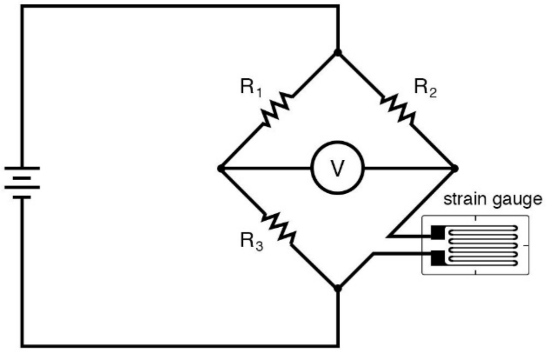

Figure 2. Quarter-bridge Type I Strain-gauge. (All About Circuits)

3. CONCLUSION

Fundamental sensor parameters were established in order to proceed with design, analysis, and simulation. A piezoelectric accelerometer was elected and defined to have a sensitivity of 1000 mV/g for a vibration signal of 0.1 g. While the strain-gauge sensor was defined to have a resistance of 350 Ω with a gauge factor of 2. In addition to the strain-gauge sensor, a quarter-bridge configuration type I proved to be suitable for development.

REFERENCES

All About Circuits. Available:https://www.allaboutcircuits.com/textbook/direct-current/chpt-9/strain-gauges/ Accessed February 20, 2022.

Ghemari, Z., Salah, S. and Bourenane, R. Resonance Effect Decrease and Accuracy Increase of Piezoelectric Accelerometer Measurement by Appropriate Choice of Frequency Range. *Shock and Vibration,* vol. 2018, p. 8, 2018

Mhlongo B. and Kallon D.V.V. Acoustics Vibration Sensing and Control Mechanism for Boilers. *Proceedings of the 11th Annual International Conference on Industrial Engineering and Operations Management,* pp 4510-4522, Singapore, March 7-11, 2021.

National Instruments Corp, 2020. Measuring Strain with Strain Gages. Available : https://www.ni.com/en-za/innovations/white-papers/07/measuring-strain-with-strain-gages.html#section-. Accessed February 20, 2022.

Shandu, P. M. and Kallon, D.V.V. A Case of Acoustics Cleaning of Industrial Boilers at Sasol Synfuels Power Station in Secunda. *Proceedings of the International Conference on Industrial Engineering and Operations Management,* pp. 2212 – 2224, Sao Paulo, Brazil, April 5 - 8, 2021

P.M. Shandu, P.M., Kallon, D.V.V., Tartibu, L.K. and R. Mutyavavire. Development Design of an Acoustic Cleaning Apparatus for Boilers at SASOL Synfuels Power Station Plant in Secunda. *South African Computational and Applied Mechanics*, pp. 900 – 909, 2019.

Biographies

Mr. T. Mafokwane attained a Bachelor of Technology in Mechanical Engineering at the University of Johannesburg (UJ) in 2017. He had earlier graduated with a National Diploma in Mechanical Engineering from the University of Johannesburg (UJ) in 2016. He has also been a tutor at the Mechanical and Industrial Engineering Technology department at the University of Johannesburg for the Computer-Aided Drawing module in 2013, and a Mechanical Engineering Drawing module in 2016 and 2017. Autodesk® Revit® Architecture certified user award conferred at Modena Design Centres in 2017. His primary research area entails vibration and strain sensor modelling and control systems engineering design.

Dr. Daramy Vandi Von Kallon is a Sierra Leonean holder of a PhD degree obtained from the University of Cape Town (UCT) in 2013. He holds a year-long experience as a Postdoctoral researcher at UCT. At the start of 2014 Dr Kallon was formally employed by the Centre for Minerals Research (CMR) at UCT as a Scientific Officer. In May 2014 he transferred to the University of Johannesburg as a full-time Lecturer and later a Senior Lecturer in the Department of Mechanical and Industrial Engineering Technology (DMIET). Dr Kallon has more than twelve (12) years of experience in research and six (6) years of teaching at University level, with industry-based collaborations. He is widely published, has supervised students from Master to Postdoctoral levels and has graduated seven (7) Masters Candidates. His primary research areas are Acoustics Technologies, Mathematical Analysis and Optimization, Vibration Analysis, Water Research and Engineering Education.