Infrared optoelectronic device for counting and measuring velocity of abrasive sponge balls used as cleaning artefacts in heat exchangers

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Abstract. Operating in the infrared range, an optoelectronic device was designed, fabricated and validated to count and measure the speed of abrasive sponge balls, used as cleaning artefacts in an innovative hydraulic system for cleaning heat exchangers without the need to shut down the turbine-hydrogenerator unit. On the one hand, the totalization of the cleaning artefacts is necessary to ensure that all injected balls have been recovered after their circulation through the inner tubes of the heat exchanger, therefore not obstructing the pathways where heat transfer takes place. On the other hand, the measurement of the velocity is critical to ensure the effectiveness of the cleaning process, proven to occur for cleaning artefacts moving with flow velocity around 2.0 m/s. Lessening false-positive counting and reducing the uncertainty associated with velocity measurements of the moving abrasive balls, the optoelectronic device discussed herein represents a significant improvement of a previous development, now operating with an improved signal-to-noise ratio and incorporating a new pair of optoelectronic sensors, all mounted on a single acrylic block, which ensures self-alignment of the optical beams.

1. Introduction
Heat exchangers play an important role in power generation. Their effectiveness is one of the factors that impact the operation of the generators. Water pumped from the turbine discharge channel, used as the cooling fluid of the heat exchanger, can often cause undesirable obstruction of the inner tubes of the exchanger as, usually, it becomes contaminated with organic materials, yielding the formation of biofouling. Such incrustations drastically damage the thermal effectiveness and the hydrodynamic performance of the exchanger, compromising the efficiency of the generator. The conventional periodic maintenance shutdowns required for cleaning heat exchangers used to cool hydrogenerators reduce productivity, causing financial losses due to equipment unavailability [1].

Ingeniously conceived, and operating in cleaning cycles, an on-line fully automated apparatus uses the cooling water of the heat exchanger to transport abrasive sponge balls —cleaning artefacts— through the tubes of the heat exchanger. Tests performed in a hydroelectric power plant [2, 3] qualified the apparatus as an efficient cleaning stratagem that avoids interruption of the generation, therefore increasing the productivity of the hydroelectric power plant. The automated system (driven by a programmable logic controller, PLC) allows for injection, recovery and washing of the abrasive balls [2] as the hydro generator operates normally.

While the alternative cleaning apparatus is discussed elsewhere [2], this paper focuses on the improved version of the optoelectronic device, designed to perform two distinct functions: (i) to generate electronic signals capable of automating the operation of the cleaning apparatus and (ii) to generate digital signals to empower the programmable logic controller, understood as the intelligence of the optoelectronic device. While the first actuates the electro valves that control the flow of the working fluid transporting the cleaning artefacts through the tubes of the heat exchanger, the latter, not only controls the number of balls introduced and recovered after each cleaning cycle but also measures the velocity of cleaning artefacts.
2. The abrasive ball counting device

The abrasive ball counting device is based on two pairs of Howeywell infrared (880 nm) photodiodes/phototransistors (SEP8736 and SDP8436, respectively), integrated in an electronic circuit implemented in a printed circuit board (PCB). Each pair of photodiode/phototransistor (positioned in the same plane but lagged 90° degrees), defines a detection region, as depicted in Figure 1a. This arrangement accounts for detection of false positives (e.g.: air bubbles; fragments of incrustation detached from the inner tube walls) so that only objects that interrupt both infrared beams are counted.

The electronic circuit [3] is responsible for exciting the photodiodes; measuring the collector voltage of the phototransistors; comparing these collector voltages with pre-set thresholds and for combining the outputs of both comparators in one digital (24 V) output that powers the PLC used to control the fully automated cleaning apparatus. As shown in Fig. 1a, this integrated enhanced system consists of two sets of identical PCBs, mounted in two parallel measuring planes of the acrylic structure, apart from a distance \( d \). Fig. 1b illustrates the Mitutoyo Linear Height Gauge device used and Fig. 1c, the experimental procedure to measure the cleaning ball travelling effective distance \( d \).

Figure 1. The abrasive balls counting device. (a) acrylic structure housing PCBs; (b) linear height gauge device; (c) measurement of effective distance \( d \)

Considering the instants of activation of each digital output —yielding the time of flight of the cleaning ball crossing both beams—, and knowing the distance \( d \) between the infrared beams, it become possible to: (i) compute the velocity of the sponge balls transported by the cooling fluid and (ii) to perform double totalization of the number of cleaning artefacts crossing each optoelectronic beam, thus improving the accuracy of the ball counting device. Regardless the importance of assessing the cleaning ball velocity —a critical parameter to ensure effectiveness of the cleaning process— its measurement allows for rejection of false positives, as any objects with linear velocity too much different from the expected values (typically 2.0 m/s) should be disregarded.

An important aspect to be considered is that the infrared beams are not very narrow. The photodiode and the phototransistor have beam angles of 10° and 18°, respectively, whilst the cleaning balls (typically having 24 mm diameter) pass through a 38.4 mm diameter acrylic duct. Thus, the detection is not based on the interruption of the infrared beam in an exact transversal plane, but rather on a gradual reduction of the infrared beam intensity until the pre-set voltage threshold is reached. This means that the ball travelling distance \( d \) should not be the measure of the distance between both the measuring planes containing the pairs of sensors, but rather the “effective distance \( d \)”, measured based on the digital outputs of the detectors.

3. Static characterization test

The static characterization test aimed at estimating the “effective distance \( d \)” between the infrared beams mounted in two parallel measuring planes. Fig. 1b illustrates the experimental setup conceived to measure it, making use of a linear height gauge (LH-600, manufactured by Mitutoyo) where one of the cleaning balls was slowly set in motion while the pulses were monitored by means of a digital voltmeter. Taking into account the classical ISO GUM procedures, a statistical analysis of thirty replicates of these measurements carried out for a confidence level of 95%, and a coverage factor given by \( k=2 \), yielded
the following results: \( d = (50.32 \pm 0.12) \) mm, as summarized in Table 1, confirming that uncertainty Type A dominates the overall uncertainty budget.

| Source of Uncertainty | Measurement Uncertainty Type A | Source of Uncertainty | Measurement Uncertainty Type B | Final Results (d = d2 - d1) |
|-----------------------|-------------------------------|-----------------------|-------------------------------|----------------------------|
| \( d_1 \) | 395.43 | 0.2391 | 0.0767 | 46.62% | \( d_1 \) | 0.01 | 1.73 | 0.0058 | 0.26% | 50.32 ± 0.12 |
| \( d_2 \) | 445.75 | 0.2450 | 0.0817 | 52.85% | \( d_2 \) | 0.01 | 1.73 | 0.0058 | 0.26% | Coverage Factor: \( k = 2.0 \)  
Confidence Level = 95.0% |

Once the effective distance is input in the software driving the programmable logic controller hardware, measurements of velocity of the travelling cleaning balls crossing both beams become possible.

4. Dynamic tests

Two dynamic tests have been performed, in two different environments: (i) in the laboratory, where the cleaning balls were introduced, vertically, into the ball counter by free fall from a height (17.4 cm), capable of ensuring velocity around 2 m/s when crossing the optoelectronic beams and (ii) in the environment of a hydroelectric power plant (Fontes Nova Power Plant), where cleaning balls were forced through the inner tubes of a heat exchanger by means of the proposed automated cleaning apparatus [2]. In both environments, independent experiments were performed to expose the ball counter device to the passage of a single ball and of two juxtaposed balls (connected to one another by means of a fine nylon thread). In both cases, the digital outputs of both measuring circuits have been recorded by a digital oscilloscope (1 MHz sampling rate; time resolution of 1 μs). Of course, the further down circuit capture a larger value of the instantaneous velocity as, in free fall, the ball accelerates with \( g = 9.79 \) m/s². The ball mean velocity crossing the counter device is then taken as the mean of both measures.

4.1. Measurements in the Laboratory environment

Figure 2a depicts the experiment performed with the single sphere dropped into the counting device (image recorded in the display of the oscilloscope) and Figure 2b shows a more detailed image of the same signals, but after they have been properly processed. In solid black line is the pulse generated by the first circuit and in grey line is the pulse produced by the second circuit (slightly higher velocity). The time lag between the beginning of the first and second pulses is 27.1 ms, yielding an average velocity of 1.857 m/s (50.32 mm/27.1 ms, whose expanded uncertainty can be estimated by the amount ± 0.12 mm/27.1 ms = 0.00443 m/s; i.e.: 0.24%).

Similarly, Figures 3a and 3b characterize the experiment performed with the two juxtaposed balls, following the same experimental procedure. As seen, the time lag between the beginning of the first double pulse and the beginning of the second double pulse is 27.5 m/s, yielding an average velocity of 1.830 m/s ± 0.00436 m/s; i.e.: within 0.24%.

Figure 2. Digital outputs generated by both PCBs (one single ball crossing beams)
4.2. Field measurements performed with the counting device installed in the cleaning apparatus

Figure 4 reproduces electronic signals associated with experiments carried out in the field environment of the hydroelectric, having the counting device installed in the automated cleaning apparatus [2], thus fully fulfilling the original purpose for which it was designed. Similarly, the counting device was able (i) to count the crossing balls without being misled by undesirable air bubbles and fragments of fouling also present in the cooling water flow and also (ii) to measure their associated average velocity. Due to space limitation, only one of the electronic signal output is presented for the field tests, for both experiments, either when just a single ball, and two juxtaposed balls, crossed the optoelectronic beams.

5. Discussion and Conclusions

The proposed ball counter device has proven to operate properly either in the laboratory as well as in the hostile environment of the hydroelectric power plant. Also assessed for possible external disturbances resulting from its operation within the hydroelectric power plant, where electromagnetic fields are always present, the circuits exhibited a reasonably good signal-to-noise ratio, while the overall optoelectronic counter proved to be immune to electromagnetic interference, whose low levels proved not to compromise the overall functioning of the counting device.

6. References

[1] T.R. Bott, Fouling of heat exchangers and its mitigation with special reference to biofouling, in: Proceedings of the 2nd European Thermal Science UTI National Heat Transfer Conference, vol. 1, 1996, pp 115–125.

[2] Frota M N, Ticona E M, Neves A V, Silva R P M, Braga S L and Valente Junior G P 2014 Experimental Thermal and Fluid Science 53 197.

[3] Nunes J, Barbosa C R H, Germano S B, Frota M N and Valente G. Infrared Optoelectronic System for Counting Spheres in Turbid Media. 2017 Proceedings of the IX Brazilian Metrology Conference (Fortaleza).