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A Feature Extractor IC for Acoustic Emission Non-destructive Testing

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***Abstract*— In this paper, we present the design and the implementation of a digital Application Specific Integrated Circuit (ASIC) for Acoustic Emission (AE) non-destructive testing. The AE non-destructive testing method is a diagnostic method used to detect faults in mechanically loaded structures and components. If a structure is subjected to mechanical load or stress, the presence of structural discontinuities releases energy in the form of acoustic emissions through the constituting material. The analysis of these acoustic emissions can be used to determine the presence of faults in several structures. The proposed circuit has been designed for IoT (Internet of Things) applications, and it can be used to simplify the existing procedures adopted for structural integrity verifications of pressurized metal tanks that, in some countries, they are based on periodic checks. The proposed ASIC is provided of Digital Signal Processing (DSP) capabilities for the extraction of the main four parameters used in the AE analysis that are the energy of the signal, the duration of the event, the number of the crossing of a certain threshold and finally the maximum value reached by the AE signal. The circuit is provided of an SPI interface capable of sending and receiving data to/from wireless transceivers to share information on the web. The DSP circuit has been coded in VHDL and synthesized in 90 nm technology using Synopsys. The circuit has been characterized in terms of area, speed, and power consumption. Experimental results show that the proposed circuit presents very low power consumption properties and low area requirements.**

***Keywords*— IoT; acoustic emission; non-destructive testing; DSP; ASIC.**

I. INTRODUCTION

Internet of Things (IoT) consists of smart devices equipped in the object, people, animals, and structures that can communicate over the Internet. IoT favors the implementation of several applications such as health care [1]–[3], smart cities [4], emergency systems [5], localization [6], gaming, UAV [7], agriculture, animal monitoring [8],[9] and other fields [10]–[22]. The Acoustic Emission (AE) method is a commonly applied Non-Destructive (ND) technique used to detect faults in mechanically loaded structures and components. If a structure is subjected to mechanical load or stress, the presence of structural discontinuities releases energy in the form of acoustic emissions through the constituting material. The AE method allows checking the integrity of a wide variety of structures by analyzing data coming from piezoelectric sensors.

One of the most common applications in this field is the testing of the structural integrity of pressure tanks. In some countries (for example Italy), the current legislation provides for the use of this technique. The actual AE method protocol is based on periodic checks that do not allow continuous monitoring and make use of very unwieldy instrumentation (Fig. 1). AE refers to the generation of transient elastic waves (Fig. 2) by a sudden redistribution of stress in a material [23], [24]. The analysis of the AE waves can be used to detect damage on structures. This method uses specific piezoelectric sensors for AE detection and electronic equipment for the signal analysis.

Fig. 1: Acoustic Emission instrumentation

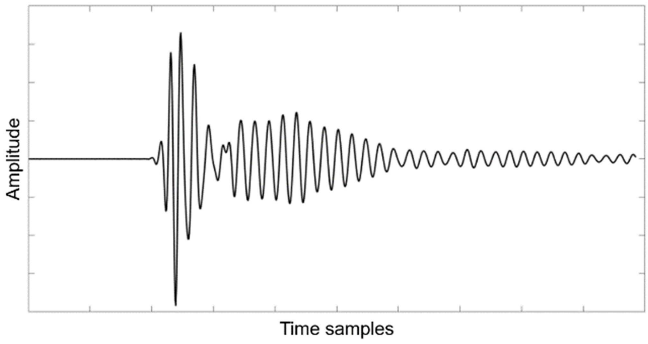

Fig.2: Acoustic Emission signal

The AE non-destructive testing method is performed analyzing some features of AE waves [23], [24]:

- the maximum of the absolute value of the amplitude;
- the signal duration;
- the signal energy;
- the number of crossings of a given threshold.

As introduced above, the present AE testing protocols are based on periodic manual checks.

Fig.3: Acoustic Emission sensor

Fig.4 Pressure tank

During the periodic checks, AE sensors (Fig. 3) are installed on the structure under test by specialized operators (Fig. 4). These sensors are wired and connected with the equipment (Fig.1) that analyses data are coming from different sensors in terms of max amplitude, duration, energy, and several threshold crossings. This approach presents two main limitations:

- The real-time monitoring is not possible, and consequently, the health state of the structure is known only during the checks.
- The current procedures require very unwieldy instrumentation.

For such reasons, the introduction of the IoT technologies in the Acoustic Emission procedure is seen as an interesting solution because it is capable of allowing real-time monitoring.

In this context, power consumption and communication channel access are crucial aspects. In a wireless channel access scheme, some critical aspects must be considered. First, the access management of a large number of devices is trying to access the access point [24] – [27]. Secondly, the exploitation of licensed electromagnetic spectrum portions (already assigned to other systems) in an opportunistic way [28-32] nevertheless in the considered application the number of IoT sensors is limited.

Using the IoT approach, the sensor will always be connected to the Internet, and real-time monitoring would be assured. To replace the present sensors with IoT sensor nodes, an important issue is the minimization of power requirements [33] – [35]. Power consumption reduction can be obtained in different ways:

- Using new technologies, in terms of devices and materials [36-38].
- Using environment aware duty cycle optimization techniques [39]
- Using mixed HW/SW solutions. For example, using hardware accelerators to reduce the computation time and consequently the energy consumption [40] – [43]
- Using design techniques at RLT level as, for example, clock gating, clock enabling or approximated operators [34], [44]
- Using techniques at the layout level as, for example, power gating [34].

Batteries or energy harvesting sources usually power IoTot nodes. This is a limitation and implies that IoT nodes cannot make use of high-speed wireless communication protocols, as the high data rates lead to high power consumption. For this reason, the node must be provided of DSP (Digital Signal Processing) capabilities to process data coming from the piezoelectric sensor. As a consequence, it can send only the AE signal features that are useful for potential damage detection and analysis through the Internet.

In recent years, such IoT sensors nodes became popular also because of the increased interest and development of Machine Learning (ML) based low-power hardware accelerators [44] – [49]. Standard ML approaches require the design of a human-driven feature extraction model to produce appropriate data for the artificial intelligence learning process [50], [51].

The identification of an AE event can be performed using deterministic approaches or statistical ones. In most of the cases, a human operator is in charge of determining the nature of the AE triggered event, whether it is real damage or a false-positive. Given the circumstances of AE non-destructive testing, we automatized the feature extraction process for the automatic classifications of the incoming signals. In this paper, we present the hardware implementation of the DSP circuits of a wireless sensor node for IoT. Such courses have been implemented in 90 nm technology and characterized in terms of area, speed, and power consumption.

II. MATERIAL AND METHODS

As discussed in the previous section, the goal of this work is the hardware design of a digital circuit that can:

- Estimate the features useful for the Acoustic Emission method.
- Send the extracted data to a wireless transceiver.

The features required for the AE method are shown in Fig. 5.

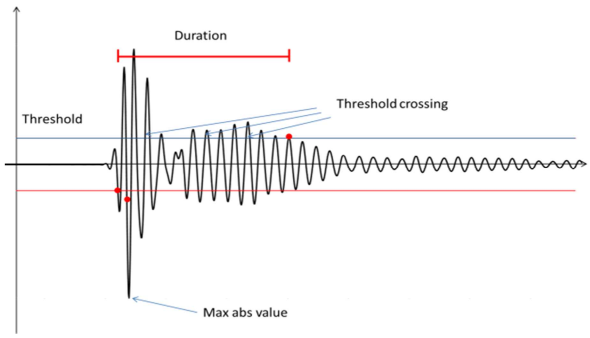

Fig.5: AE signal features

In the following subsections, we analyze the algorithms and the circuit used for the features estimation and the communication interface among the DSP circuit and the wireless transceiver.

A. Duration

The Duration of an AE signal is defined as the time interval between a start time and a stop time. The start-time corresponds to the moment in which the module of the signal is above a certain threshold. The stop-time is the instant when the signal goes below the threshold and maintains a lower value for at least 200 μs. This time is called DDT.

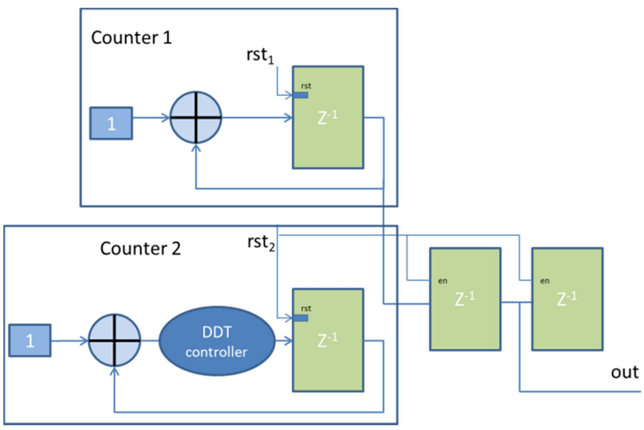

Fig.6 Circuit for the duration estimation

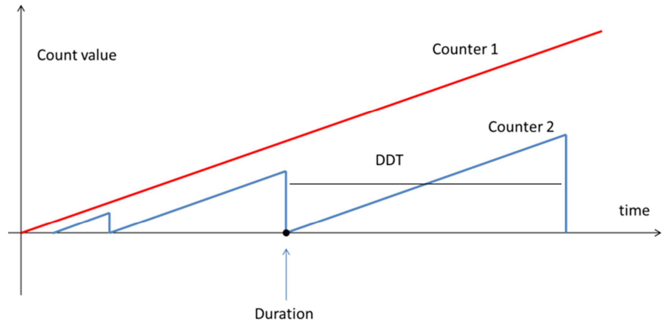

Fig. 7 Duration estimation

The duration estimator circuit has been implemented by two counters and a control logic net (Fig 6). The computational process of such an operation is shown in Fig. 7: when the absolute value of the signal exceeds a given threshold, the first counter (Counter 1) start to count. From this moment on, every time the signal goes below the threshold a second counter is reset, and it starts to count. This second counter is designed to count until 200 μs (the DDT time). If this counter reaches the DDT, the event is considered finished, and its duration corresponds to the previous second counter reset time. Vice-versa the second counter restart. Figure 8 shows the duration estimation circuits, composed of the two counters and the additional control logic.

B. Number of threshold crossings

The number of threshold crossings is defined as the number of times that the positive part of the signal goes across (below to above) the threshold, as shown in Fig. 5. This feature is estimated using the circuit shown in Fig. 8, which is composed of two delay blocks, two comparators, and a counter.

The circuit works as follows: the present and the previous values of the signal are respectively at the input and the output of the upper delay. Such values are compared with the threshold. If the signal goes across the threshold, the two comparators output is respectively 1 and 0. When the crossing event occurs, the AND logic gate (with a negated input) provides 1 to the enable input of the counter that increments its value that corresponds to the number of threshold crossings.

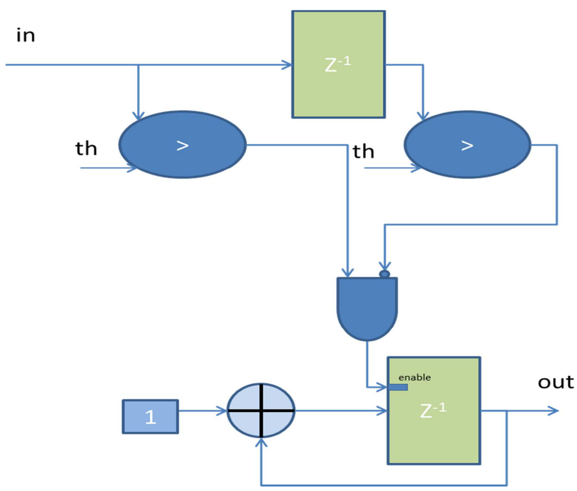

Fig. 8: Circuit for the number of crossings counting

C. *Max Value*

The maximum of the absolute value of the AE signal is another signal feature required for the AE diagnostic method. This value is estimated using the circuit shown in Fig. 9. The circuit is composed by a comparator, a delay, a multiplexer, and an absolute value net. The absolute value of the present value of the input signal is compared with the value stored in the delay that represents the present maximum (the comparator performs this operation). If the sample at the input is greater than the previous max value stored in the delay block, the newer sample becomes the new AE signal maximum.

D. *Energy*

The energy of the AE signal is defined in Eq.1

$$E = \sum_{start\_time}^{stop\_time} |x[n]|^2 \quad (1)$$

The energy estimator has been implemented using a digital integrator and a multiplier for the power of two operations. The energy is computed in the time interval defined by the start time and the stop-time of the AE signal.

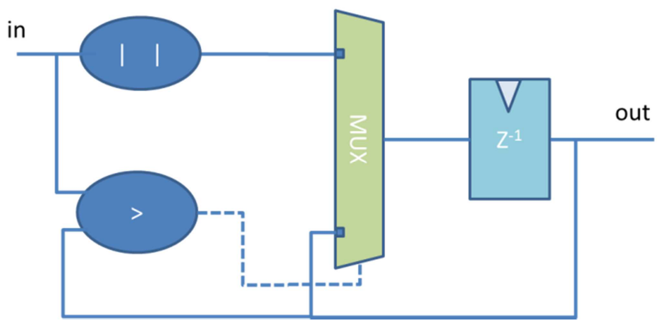

Fig. 9: Circuit for the maximum estimation

E. *IO Interface*

To communicate with other devices, the proposed circuits have been equipped with an IO interface. For this purpose, an SPI interface has been chosen. The communication procedure works as follows: when the DSP circuit ends the AE signal processing, a ready signal is asserted, and after one clock cycles the features are sent to the transceiver using the SPI protocol.

III. Result and Discussion

After a fixed-point optimization performed on MATLAB/ Simulink, the above-discussed system has been coded in VHDL (VSIC Hardware Description Language) at RTL abstraction level and then synthesized. The synthesis was performed by Synopsys Design Compiler using the STM 90 nm library of standard cells. Based on the results of the MATLAB/Simulink simulation, the system input and output dynamic range are 10 bits. Considering the narrow bandwidth of AE sensors used for non-destructive diagnosis, the clock frequency constraint was set to 5 MHz.

TABLE I
Implementation Results

Total cell area	10508.8 μm^2
Clk Freq.	5 MHz
Total Dynamic Power	35.3 μW
Cell Leakage Power	1.2 μW
Total Power consumption	36,5 μW

The power consumption analysis (at 5 MHz) shows that the cell leakage power is 1.2 μW against the 35.5 μW relatives to the total dynamic power. Being the Cell leakage power only 3.4% of the total Power consumption, the employment of Power gating to further reduce power consumption would not be justified. This is because, as shown in Fig 10, the power gating introduces a sizeable overhead (sleep transistors, isolation gates and extra routing for the sleep and isolate control signals as shown in [34]). Considering the results shown in Tab. 1, such additional complexity is not justified.

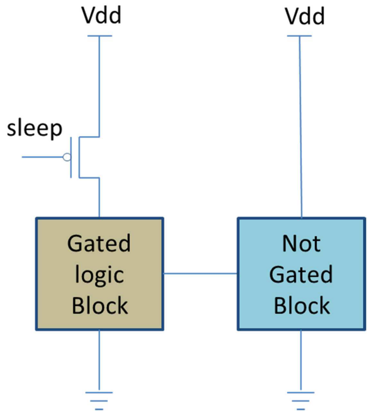

Fig. 10 Power gating by sleep transistor insertion

IV. Conclusions

In this paper, we presented a DSP STM 90nm ASIC circuit of an IoT node designed for Acoustic Emission analysis. The proposed circuit can extract the features needed for the AE diagnostic method from the AE signal. The results show a much reduced area and limited power consumption. The total power consumption during the computation is only 35.3 μW. The system is feasible for its use in IoT-based sensors environment approaches. The sensors will always be connected to the Internet and the real-time monitoring is assured.

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