

## AUTO-SCALING FIELD SENSORS BASED ON THE MAGNETOSTRICTIVE DELAY LINE TECHNIQUE

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**Abstract** – In this paper, we present new auto-scaling field sensors based on the magnetostrictive delay line (MDL) technique. The principle of operation is based on the variation of the magneto-elastic response of an array of MDLs with respect to the applied input, which depends on the composition and the annealing history of the material.

Keywords: Magnetostrictive delay lines, sensors, auto-scaling sensors.

### 1. INTRODUCTION

Sensors play an important role in engineering. A vast variety of applications in automotive industry, medicine, military, environmental engineering and other fields of applications, are using sensors as the principal or secondary means for the controlling and reacting process [1]. Sensitive field sensors are of additional importance. The most sensitive field sensors are the superconducting SQUIDS, able to detect with a sensitivity of 1 fT, having though the disadvantage of being extremely expensive and difficult to be used. An industrially used field sensor with a sensitivity of 100 pT is the fluxgate field sensor [2], which is used in many applications. The motivation of this work was the realisation of a sensor combining good sensitivity of the order of 100 pT in a range of measurement up to 0,1 T. The sensing principle is based on the magnetostrictive delay line (MDL) technique [3], according to which we are able to arrange automatically the range of the under measurement magnetic field. In this paper we shall present a sensing device able to perform unhyseretic measurement of field with sensitivity of 1 pT within a range of 100 mT.

### 2. MDL MODELING

In order to present our MDL modeling, we start with the simplest possible arrangement, shown in Figure 1. Concerning this set-up, the transient field  $H(x,t)$ , along the length of the MDL, transmitted via the coil is:

$$H(x,t) = f(x)I(t) = \frac{1}{\sqrt{a^2 + x^2}} I(t)$$

The transient current  $I$  is assumed to be a rising ramp from 0 to  $I_0$  for  $0 < t < n_1 T$ , a steady state current  $I_0$  for  $n_1 T < t < n_2 T$  and a falling ramp from  $I_0$  to 0 for  $n_2 T < t < n_3 T$ , where  $T$  is the time increment and  $n_i$  integer numbers. Having applied the field  $H(x,t)$ , the rotation of the magnetic moments of the outer cell of the magnetic domains of either the positive or the negative magnetostrictive wire towards the direction of  $H(x,t)$ , results in microstrain generation. We have experimentally found that such transient microstrain has an almost un-hysteretic behavior due to the small hysteresis of the B-H loop of the wire. In order to model such microstrain dependence we conceived the following equation:

$$\lambda(H) = \lambda_s (1 - e^{-cH^2}), c > 0$$

Such microstrain dependence is in good agreement with the micromagnetic modeling dependence of  $\lambda \sim aM^2$  after analyzing it in a Taylor series. The microstrains  $\lambda(x,t)$  caused by the rising transient current are summed up as a group of strains  $Gr(x,t)$ :

$$Gr(x,t) = \sum_{n=1}^{n_1} \lambda_s (1 - e^{-c \frac{(\frac{nI_0}{n_1})^2}{a^2 + (x - (n_3 + n_2 + n_1 - n)Tv)^2}})$$

With  $v$  the longitudinal sound velocity of the MDL. The microstrains  $\lambda(x,t)$  caused by the steady state transient current are summed up as a group of strains  $Gs(x,t)$ , which follows  $Gr(x,t)$ :

$$Gs(x,t) = \sum_{n=n_1}^{n_2} \lambda_s (1 - e^{-c \frac{(I_0)^2}{a^2 + (x - (n_3 + n_2 - n)Tv)^2}})$$

Finally, the microstrains  $\lambda(x,t)$  caused by the falling transient current are summed up as a group of strains  $Gf(x,t)$ , which follows  $Gs(x,t)$ :

$$Gf(x,t) = \sum_{n=n_2}^{n_3} \lambda_s (1 - e^{-c \frac{(\frac{(n-n_3)I_0}{n_3})^2}{a^2 + (x - (n_3 - n)Tv)^2}})$$

These groups of microstrains propagate along the magnetostrictive wire as an elastic pulse. This elastic pulse causes a flux change along the volume of the material it propagates, which is can be detected by a search coil.

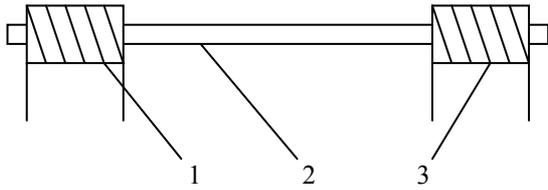


Fig. 1. The schematic of the MDL set-up. (1) Excitation coil, (2) MDL, (3) Search coil.

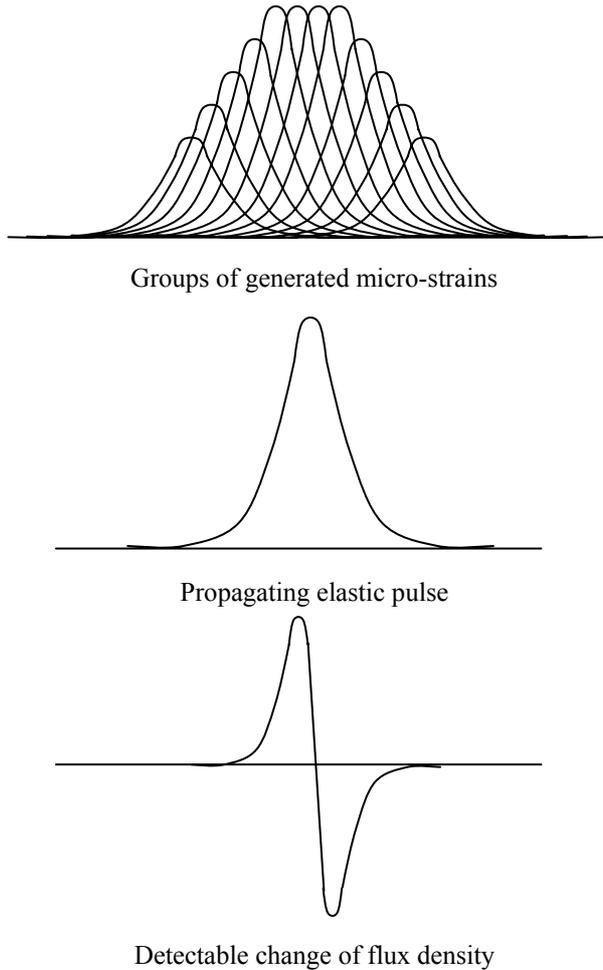


Fig. 2. Generated, propagating and detected micro-strains by means of pulsed voltage output: case of a short excitation field.

Suppose that the pulsed transient current is short, then the change of the flux in the wire gives a single pulsed voltage output, as illustrated in Figure 2. If the pulsed current has a long steady state, then the first derivative of the elastic pulse, which corresponds to the pulsed voltage output breaks into two pulses, opposite in signs which are detected by the search coil, as illustrated in Figure 3.

We performed numerical calculations of the elastic pulse groups and their first derivatives. We have also experimentally tested the amorphous wire using the arrangement of Figure 1 and we have had an agreement of

97% between the modeling calculations and the experimental results. This fact suggests that we can continue our modeling for the MDL sensor arrangements.

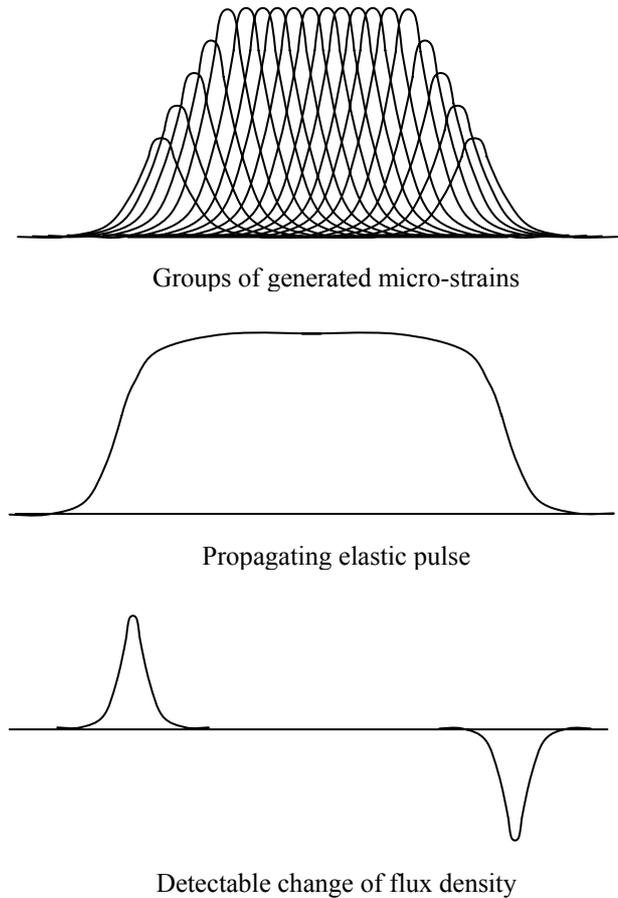


Fig. 3. Generated, propagating and detected micro-strains by means of pulsed voltage output: case of a long excitation field.

### 3. THE MDL FIELD SENSORS

The operation of the MDL technique has been illustrated in Figure 1. An excitation coil is used to transmit pulsed current and therefore pulsed field along a magnetostrictive fiber. Such pulsed field generates a strain due to the magnetostriction effect. Such strain propagates as elastic pulse re-orientating the direction of the magnetic domains as it passes by, due to the inverse magnetostriction effect. Such re-orientation results in a transient voltage response at the output of a coil, set along the MDL. The magnitude of the generated strain and the detected output depends on the amplitude of the ambient field, the pulsed current waveform and the magnetostrictive element itself. Having kept all parameters constant but the ambient field we can modify the response of MDL with respect to the ambient field. Therefore, such an MDL device can be used as a field sensor. Performing field calibration experiments, a sensitivity uncertainty of 100 nT in the range of 0-0,1 T, has been determined after stress current annealing [4].

#### 4. EXPERIMENT

The response of the field sensor is mainly dependent on the magnetostriction function  $\lambda(H)$ , also known as butterfly curve. Tailoring the  $\lambda(H)$  function of the material results in modification of the magneto-elastic response with respect to either the applied stress or ambient field. Therefore, if an array of MDLs, having undergone different annealing treatment, is subject to the ambient field along their length or the displacement of a permanent magnet or the tensile stress along their length, the corresponding magneto-elastic response of each MDL will be dependent on the history of the material. This way, the largest response corresponding to a given magnetostrictive wire can be chosen at the time to accurately detect this input.

For this reason we performed the following experiment. Three  $\text{Fe}_{78}\text{Si}_{17}\text{B}_{15}$  magnetostrictive wires were annealed under magnetic field, resulting in magneto-elastic saturation fields of 10, 100 and 1000 A/m respectively, named as W1, W2 and W3 wires respectively. Their response under ambient dc field was monotonic. A representative response of one of the wires is illustrated in Figure 4. The sensitivity levels of the three different wires W1, W2 and W3 are illustrated in Table 1. Such response suggests that simultaneous use of these three wires can detect with distinguished accuracy magnetic fields.

One way to use such result is to arrange them parallel each other in the classical MDL arrangement, using one excitation and one search coil per delay line. A microprocessor based circuit controls the excitation current and the readouts of the search coils. The arrangement is subject to ambient field. The electronic circuit selects the largest response in amplitude corresponding to the closest range of measurement and consequently determines the applied biasing field along the wire.

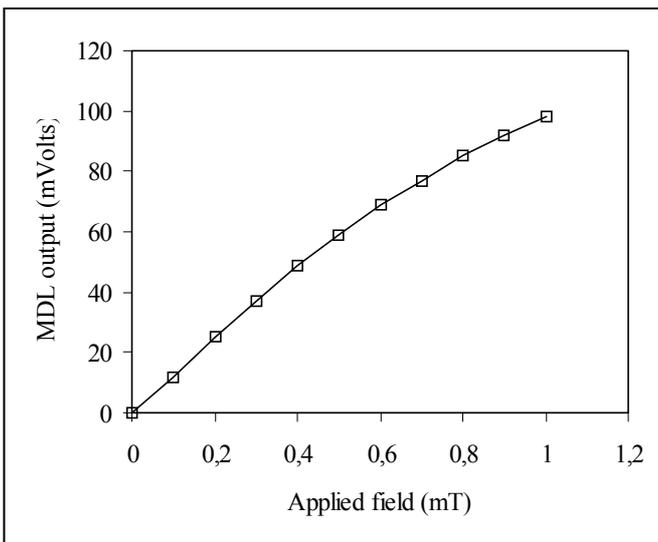


Fig. 4. Illustrative response of the MDL field sensor using the wire W1.

Such idea can also be used in mechanical sensors like position sensors. Using wires under different annealing

conditions one can realize position sensors, which can detect different ranges of measurement. We are in the process of applying such idea in position and stress sensors.

Table 1. Levels of sensitivity of the three different wires.

	Sensitivity	Uncertainty	Range
Wire W1	100 pT	100 ppm	1 mT
Wire W2	1 nT	80 ppm	10 mT
Wire W3	10 nT	150 ppm	100 mT

#### 5. THE SENSOR ELECTRONICS

The architecture of the hardware is depicted in Figure 5. The signal from the sensor input, is amplified and fed to a 10 MHz low pass filter. The amplified signal drives a comparator. The comparator tracks when the signal exceeds a predefined threshold. The analog part consists also of two peak hold circuits and a peak detector. There is also a 80 MHz clock and a counter that counts the time from the start until the positive peak of the signal. The peak hold circuits and the counter is controlled by an asynchronous control logic. The MCU samples the positive and negative peak amplitude and the counter value and sends the information to a PC through the serial port interface. It also drives the Power SW for the excitation voltage of the sensor.

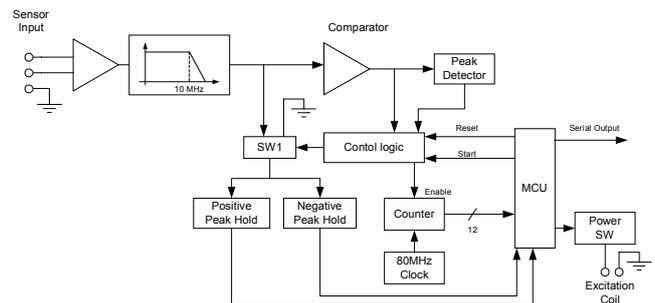


Fig. 5. The architecture of the hardware.

The amplifier consists of standard instrumentation amplifier with a suitable termination circuit at the input. The signal is amplified approximately 100 times and the bandwidth of the amplifier is 10 MHz. The filter is a simple RC low pass filter with a 10 MHz corner frequency. The comparator signals when the amplitude is higher than a predefined positive threshold level. This comparator output is used to control the peak hold circuits. When the level of the amplified signal exceeds the threshold than a monostable multivibrator is triggered. The output of the multivibrator controls the switch SW, by feeding in the peak hold circuits the amplified signal. The output of the multivibrator is held high for only a few  $\mu\text{s}$  and then the input of the peak hold circuits are tied to ground. The peak detector, produces a short negative pulse whose rising edge coincide with the signals maxima. This signal is used to stop the counter. The peak hold circuit tracks their input and lock on the maximum (positive peak hold circuit) and the minimum (negative peak hold circuit) of the input signal. The value is

held until the MCU clears the hold capacitors with a proper reset. Special care has been taken for the peak hold circuit to respond to the steep input signal and to have low leakage current. The time elapsed from the excitation pulse until the positive maximum of the signal is measured with a 12-bit counter and a 80 MHz clock giving us a 12,5 ns accuracy.

The main purpose of the control logic is to control the peak hold circuits and the timer and to lock their values when the input signal is received. The logic is asynchronous triggered by the edge of the signals, having a sufficient fast response. The MCU initiates every measurement session and transfers the acquired data to a PC through the serial port. The data consists of a 12-bit number from the counter and two 10-bit samples from the peak and hold circuits. The data is packed together with a header and a CRC and send through the serial port at 115kbaud. In order for the described system to work, two different pieces of software were implemented: one that runs on the embedded microcontroller and one for the host pc. On the rest of this document we give a brief description of the architecture of this software.

The block diagram of the microcontroller firmware is shown in Figure 6. As seen on this diagram, after the power-up of the system, the microcontroller is initialized. On this phase all basic system initializations are being performed for the I/O ports of the microcontroller, the A/D module specifications (10-bit operation, bit-alignment, sampling properties), the USART module (Baud rate selection at 115200, 8N1) and the internal microcontroller timer for timeouts. After initialization the system is kept in a state where all external peripherals (external counter, peak-hold circuits) are kept on initial reset state. In this phase the stimulus pulse is generated. This pulse according to our specifications is kept high for duration of 1 $\mu$ s and must remain low for the remaining of the stimulus pulse period. This period is equal to 1ms and during this period all remaining actions must be performed. On the present state we generate only the 1 $\mu$ s positive pulse, which is externally interfaced to the stimulus coil and then the output of the microcontroller driven to the stimulus coil is set to zero for the remaining of the period. After the generation of the positive pulse, a fixed short delay of 2  $\mu$ s is produced before proceeding. This delay is needed in order for the analog reception circuits to reach steady state and to be able to perform any peak detection and measurement. During this phase the external counter is also enabled (starting from zero since it was previously reset) in order to measure the time of the positive peak occurrence.

After the stimulus pulse is generated, we enter on a wait-loop in which a signal from the peak detect circuits is awaited. When this signal arrives the microcontroller immediately pauses and reads the counter value. If no peak detect signal arrives within a timeout period of 900  $\mu$ s, the microcontroller exits this state and returns to stimulus-pulse generation phase, after having performed a reset of the external counter and all peak-hold circuits and having transmitted the appropriate error code values to the host pc. During this phase the microcontroller measures the peak values from the peak-hold circuits using it's A/D converter (2 channels for each of the positive and minus peaks).

As explained in other part of the document, the peak detect circuit detects the first encounter of a positive peak. Using this software architecture we assume that the time until the A/D begins measurement of the negative peak is sufficient for this peak to have occurred. However taking into account the delay until the microcontroller A/D measures the positive peak as well as any other delay of the execution of all other instructions (including an adequate delay in order to set up its A/D channel select switches) it's sure that the negative peak will have occurred until the microcontroller measures from the negative peak channel. After the data acquisition, the external counter is also reset. On this phase the previously measured data (time from stimulus pulse until positive peak detection, amplitude of positive peak and amplitude of negative peak) are combined into 4 bytes of data (12 bits for the counter + 2\*10 bits for each sampled peak value = 32 bits). Then a data packet that consists of a standard header, the 4 bytes of data and a 1-byte CRC is formed and it is transmitted from the microcontroller through its USART interface to the connected host pc at 115200 bps. Since the packet consists of a total of 48\*10 = 480 transmitted bits (including start + stop bits) a time of 480/115200 = 4.1ms is required to transmit each data packet. This means that transmission has to be completed asynchronously to the collection of data, in order to maintain 1ms cycles. If we want real time continuous loop operation, up to 240000 measurements per second can be conducted.

The last phase is needed in order to ensure a 1ms period until the stimulus is repeated when the program loop is repeated without any further delays. Of course in our operation, where a continuous rs-232 transmission is used, it is impossible to overcome 240Ksamples/sec. Thus this delay loop is not strictly necessary. However we have included this delay in order to be accurate even in the case of continuous operation where some processing (i.e. filtering) is needed and fewer bytes are transmitted via rs-232 (i.e. a mean time each 10 measured values). It is obvious that such a feature would require modification of the presented scheme in order to include all necessary processing before data transmission phase. After the 1ms delay phase completes, the software waits until time for next measurement arrives and returns to the stimulus pulse generation phase to repeat itself. The whole operation of the system can be initiated and halted any time from the host pc, using corresponding commands sent via the serial rs-232 connection.

The software of the host PC is developed for the Operating System of Microsoft Windows™. All 32-bit Windows™ platforms are supported (Windows™ 95/98/NT/2000). With the corresponding software, the host PC initiates the operation of the connected board by sending a specific byte via RS-232. Then the board begins operation sending each time the three packed values of data. The PC receives each data packet and unpacks the measured values. Digital Signal Processing including adequate filtering is then being performed on the PC side in order to extract the actual position of each detected crack and present an easily understandable output. The result is presented to the user both graphically and numerically: the position of the

detected crack is plotted in the form of a 2-D graph where the x-axis represents the position of the detected crack (in the axis of the sensor) while the y-axis represents the value (amplitude) the system detected, according to the system's specifications. Also the position is shown numerically by providing two large sized digits in the application window, one for the x-axis position and one for the y-axis position.

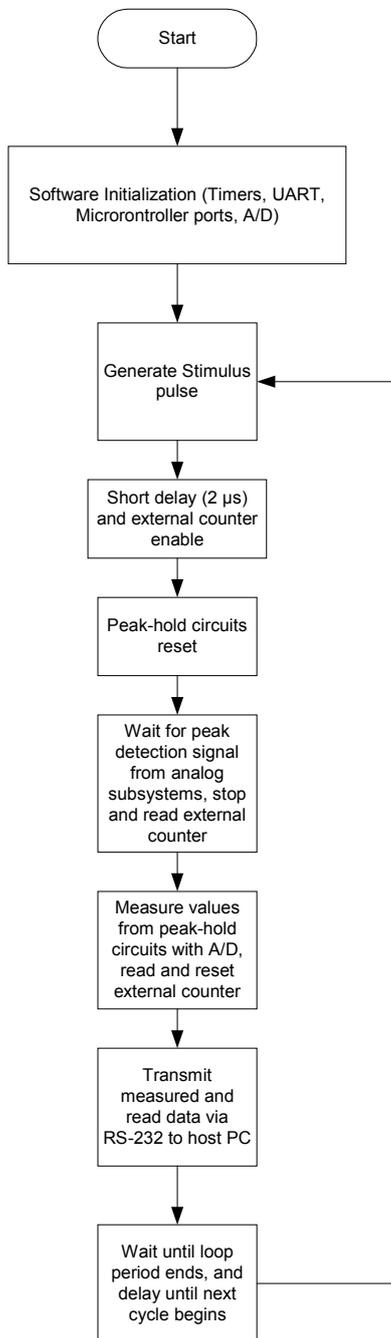


Fig. 6. The firmware of the circuit.

The above system is considered a prototype and currently we plan to design a miniature signal conditioner together with the measurement and processing unit. The diagram illustrated in Figure 7 reveals the hardware architecture for the proposed future implementation. The analog part of the hardware is kept to a minimum. We only use an amplifier for the sensor and a power switch for the excitation voltage. The output of the amplifier is sampled by a A/D converter and stored in the DSP memory. The DSP processes the data and with proper software detects the peaks, or even specific patterns. We plan to have two different interfaces. A serial port interface, (RS-232 or RS-485) to easily interface the system with a computers or embedded systems and a graphic LCD port to easily make the proposed system a handheld measurement system.

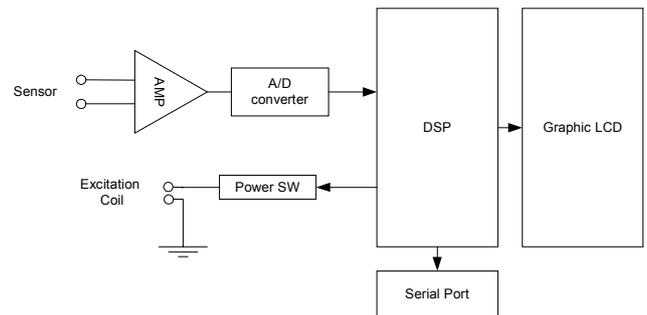


Fig. 7. Future hardware implementation.

## REFERENCES

- [1] Mohri, K., Kasai, K., Kondo, T., Fujiwara, H. and Matsumoto, M.: "Magnetometers Using Two Amorphous Core Multivibrator Bridge", *IEEE Trans. Mag.*, 19, pp. 2142-2144, 1983.
- [2] E.O. Doebelin, "Measurement Systems: applications and design.", fourth edition, McGraw-Hill, 1990.
- [3] E. Hristoforou, "Magnetostrictive delay lines and their applications", *Sensor and Actuators A*, 59, pp. 183-191, 1997.
- [4] E. Hristoforou, H. Chiriac, M. Neagu, "A new magnetic field sensor based on magnetostrictive delay lines", *IEEE Trans. Instr. Meas.*, vol. 46, pp. 632-636, 1997.

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