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# An adaptive channel equalization algorithm for MFL signal

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ABSTRACT

Magnetic Flux Leakage (MFL) method is one of the most robust non destructive evaluation (NDE) techniques employed by in-line inspection (ILI) tools such as an instrumented pipeline inspection gauge (IPIG), to assess the health of buried cross country pipelines, carrying petroleum products. An array of hall-effect sensors disposed ideally at the magnetic neutral plane of a permanent magnet resident in IPIG, cling to the inner surface of the pipe wall, measuring the change in leakage flux density. However, ideal sensor disposition is almost never satisfied and each sensor measures differently. In this paper, a new scheme of channel equalization is proposed for MFL signal so as to correct sensor misalignments, which eventually improves accuracy of defect characterization. Also, for the above, a baseline estimator is developed, which estimates the baseline of MFL sensor output signal under pipeline defects and key features (wields, sleeves, valves). The scheme proposed is adaptive to the effects of error in the disposition of the sensor due to manufacturing imperfections and sensor movements (bounce/axial shift near a weld). The algorithm is tested on field data acquired by an IPIG running in a commercial pipeline. The final result obtained shows excellent signal recovery and noise cancellation.



## 1. Introduction

MFL technique is one of the most widely used NDE methods for pipeline inspection. An IPIG, used for MFL inspection (MFL-IPIG), consists of strong permanent magnets that magnetize a segment of the carbon steel pipeline axially to near saturation. An array of circumferentially disposed hall sensors senses the axial and/or radial component of the leakage flux. Details of construction of an MFL-IPIG magnet assembly, showing sensor disposition can be found in reputed IPIG manufacturers' web sites as well as in literature on MFL tool and technology [1,2]. The sensors are located at the magnetic neutral plane (i.e. at mid-point of north and south poles) of IPIG's permanent magnet assembly. Any change in the thickness of the pipe wall, as a consequence of defects or pipe features, is reflected as a change in the leakage flux strength and is sensed by the hall sensors [3,4]. Ideally, the hall sensors cling to the inner surface of the pipe wall. However, non ideality of manufacturing process (variation in wear plate thickness, sensor placement in the sensor-mold, length of sensor arm, spring stiffness, etc.) and working conditions (sensor bounce caused by a sharp bend or a rough patch) may result in non deterministic lift-off and slight drooping of the spring-loaded sensor arms. Moreover, there could be an axial shift in the sensor position due to the change in pipe thickness, weld protrusion, etc. In either case, sensors are no more at the magnetic neutral plane. The former causes the sensors to record a lower level of leakage flux while the latter causes change in the MFL signature around a defect or feature. As each sensor in the array is independently affected by the above mechanisms, the final 2 dimensional (2D) image (gray scale representation) [5] of the pipe section becomes cluttered and extremely difficult to interpret. It is observed experimentally that this effect is more severe for the radial component of leakage flux, and hence this paper deals with the radial component only. However, the proposed method can as well be applied to axial flux leakage signal.

The sensing arrangement, that is, each sensor, its mechanical support and the underlying electronics for acquiring the leakage flux data, commonly referred to as a channel, suffers mismatch among each other. Such channel-to-channel mismatch is commonly encountered in array processing and can be equalized using adaptive techniques. Channel equalization techniques are exhaustively used to deal with distortion and inter symbol interference in communication channels, bringing their states at par [6]. An adaptive channel equalization algorithm to address the issues related to MFL signals have been discussed in [7], however, under the assumption that at least one sensor out of the sensor array is ideal and can be accepted as reference. For implementation however, this assumption imposes serious limitation on the performance of post processing algorithm as tolerance and misalignment of an individual sensor is not deterministic and needs

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to be accounted for in a stochastic framework for choice of a clear cut candidate qualifying as a reference channel.

In this paper, a new adaptive channel equalization algorithm to minimize channel-to-channel mismatch is proposed for MFL signals. In contrast to [7], the reference signal required for channel equalization, here, is the baseline estimate of the same channel reflecting the background leakage flux. As the baseline under a defect/feature signal is not available from measurement, it is estimated by first order forward or backward prediction of neighboring MFL data. It may be noted that the reference signal corresponds to the signal that would have been sensed from a virgin pipe (without any defect/feature). For equalization of channels, the reference signal for each channel needs to be brought to a desired level, which can be computed a priori (for a virgin pipe) assuming all ideal conditions for the channel. One can adaptively model a system that transforms the derived reference to the desired output. The identified system in fact, can be shown to be the inverse of the system responsible for inflicting all the signal anomalies discussed above and hence could be used to negate the effects of such misalignments. An adaptive least mean square (LMS) error minimization scheme is used for identification of the inverse system, which is then employed on the actual MFL sensor measurement to obtain the desired response. The result obtained portrays the MFL signal for sensors stationed at ideal conditions.

The paper is organized as follows. Section 2 deals with the theory of the proposed channel equalization scheme. In section 3, baseline estimation algorithm is developed. Section 4 discusses the LMS minimization for adaptive channel equalization and resulting 2D representation of the pipe section. Sections 3 and 4 also includes the results reflecting the performance of the proposed algorithms on field data. Section 5 concludes the paper indicating major achievements and future scope of this work.

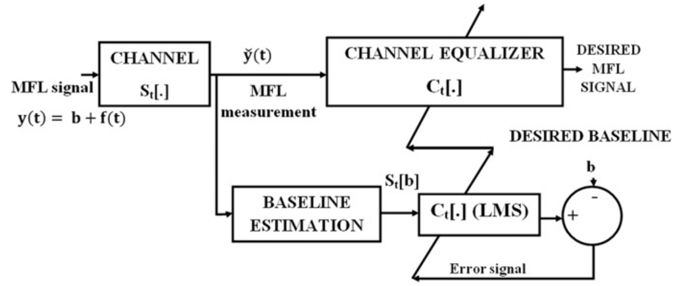


Fig. 1. Overview of the channel equalization scheme.

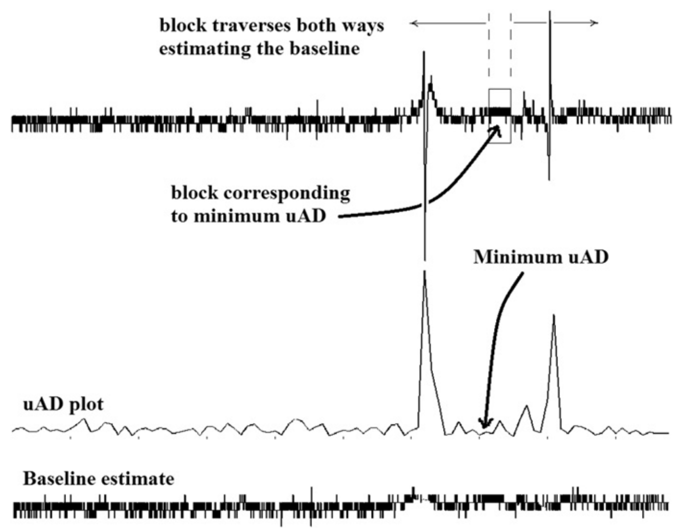


Fig. 2. Baseline estimation.

## 2. Overview of proposed method of channel equalization

To begin with let us formally define a channel.

**Channel**: A channel is a system consisting of a sensor, its mechanical carriage assembly, electrical connections to the data acquisition system and electronics for acquisition of MFL data (anti-aliasing filter and analog-to-digital converter (ADC)).

The MFL sensors have two degrees of freedom, axial movement and tilt. These two along with noise due to sensor bounce, quantization error, etc can be considered as the states of the system. Dynamic behavior of each sensor channel is decided by the way the system states move in the state space. It is assumed here, that each state is independently reflected in the output and hence the present system can be considered as observable. For an observable system, each of the states can be estimated from the output (MFL measurement in this context), $\tilde{y}(t)$, and hence can be corrected [8]. System states can be computed as shown below.

$$x(t) = M^{-1}(T,t) \int_t^T \phi^T(\lambda,t) C^T(\lambda) \tilde{y}(\lambda) d\lambda \tag{1}$$

where, $M(T,t)$ given by $\int_t^T \phi^T(\lambda,t)C^T(\lambda)C(\lambda)\phi(\lambda,t)d\lambda$, is the observability grammian matrix, vector $x(t)$ denotes the states of the time varying system, $\phi$ denotes the state transition matrix and $C$ (not necessarily non singular) denotes the measurement matrix. If observability grammian is non singular, initial state $x(t)$ can be found, given $\tilde{y}(t)$ over the interval of the integral $[t,T]$. A future state can be computed by extrapolating initial state $x(t)$. As system states can be computed from past observations, it is argued that they can also be corrected (to equal those of an ideal system) by an equalizer such that final output observation matches with that of an ideal channel. In view of the above discussion, a correction scheme is proposed as given in Fig. 1.

Let the ideal MFL output signal be $y(t)$, which is the addition of the ideal baseline,$b$ and pipeline defect/feature signal for an ideal channel, $f(t)$. Thus

$$y(t) = b + f(t) \tag{2}$$

Let $S_t[.]$ be a time-varying linear operator representing a sensor channel such that the measured MFL signal $\tilde{y}(t)$ is given by

$$\tilde{y}(t) = S_t[b + f(t)] \tag{3}$$

$$\Rightarrow \tilde{y}(t) = S_t[b] + S_t[f(t)] \tag{4}$$

Thus, $S_t[.]$ is responsible for the shift of the states from the ideal values. Note that $S_t[b]$ presents the baseline of the measured MFL signal $\tilde{y}(t)$ and can be estimated from it. Let this estimate be $\tilde{b}(t)$, which represents the measured MFL signal for the same pipe segment virtually eliminating all defects/features from it. This pipe segment can now be viewed as a virgin pipe whose desired baseline is known a priori to be $b$.

From the baseline estimate $\tilde{b}(t)$, we compute an inverse time varying system that transforms $\tilde{b}(t)$ to its ideal value $b$ Let this inverse system be represented by a linear operator $C_t[.]$ Hence

$$b = C_t[\tilde{b}(t)] \tag{5}$$

$$\Rightarrow b = C_t[S_t[b]] \tag{6}$$

Thus $C_t[S_t[.]]$ forms an inverse mapping system. Operator $C_t[.]$ when acts upon a signal operated by $S_t[.]$ retrieves back the