PIPELINE MECHANICAL DAMAGE CHARACTERIZATION

BY MULTIPLE MAGNETIZATION LEVEL DECOUPLING

Richard J. Davis & J. Bruce Nestleroth
Battelle
505 King Ave
Columbus, OH 40201

INTRODUCTION

Mechanical damage, caused by mechanical forces that deform the natural cylindrical shape of a pipe, can be detrimental to the operational integrity of a pipeline. Mechanical damage can either remain benign for the operational life of the pipeline or lead to failure. Mechanical damage is the leading cause of pipeline failures in the United States. Therefore, it is important to both detect mechanical damage defects and characterize parameters such as microstructure change, residual stress, and the extent of removed metal.

Magnetic flux leakage (MFL), the most commonly used technique for the nondestructive examination of pipelines, uses a single magnetization level to detect pipeline anomalies. Prior work has shown that the flux leakage signal from various anomalies is a function of magnetization level [1-2]. As illustrated in Figure 1, flux leakage from geometric changes, such as denting, metal loss, and wall thinning, can be isolated at high magnetization levels, usually well above the knee of the magnetization curve. Flux leakage signals from anomalies that change the magnetic properties, such as cold work, plastic deformation, and residual stress, are better detected at low magnetization levels usually near the knee of the magnetization curve. Unfortunately, the geometric portion of the anomaly is also contained in the flux leakage signal acquired at low magnetization levels. A multiple magnetization level approach has been developed to isolate information from both types of anomalies. Classifying and sizing the damage requires additional signal processing. The measured signals must be decoupled into their geometric and magnetic components. Once decoupled, the unique signatures become more readily apparent.

DECOUPLING

There is an optimum magnetization level where the effects of magnetic deformation are greatest. This point is below the knee of the B-H curve, between 50 and 70 Oersteds. At high magnetization levels, at or above 150 Oe, the effects of magnetic deformation disappear. A signal measured at the lower magnetization level contains information on both the geometric and magnetic deformation. It is referred to as a mixed signal. At a high

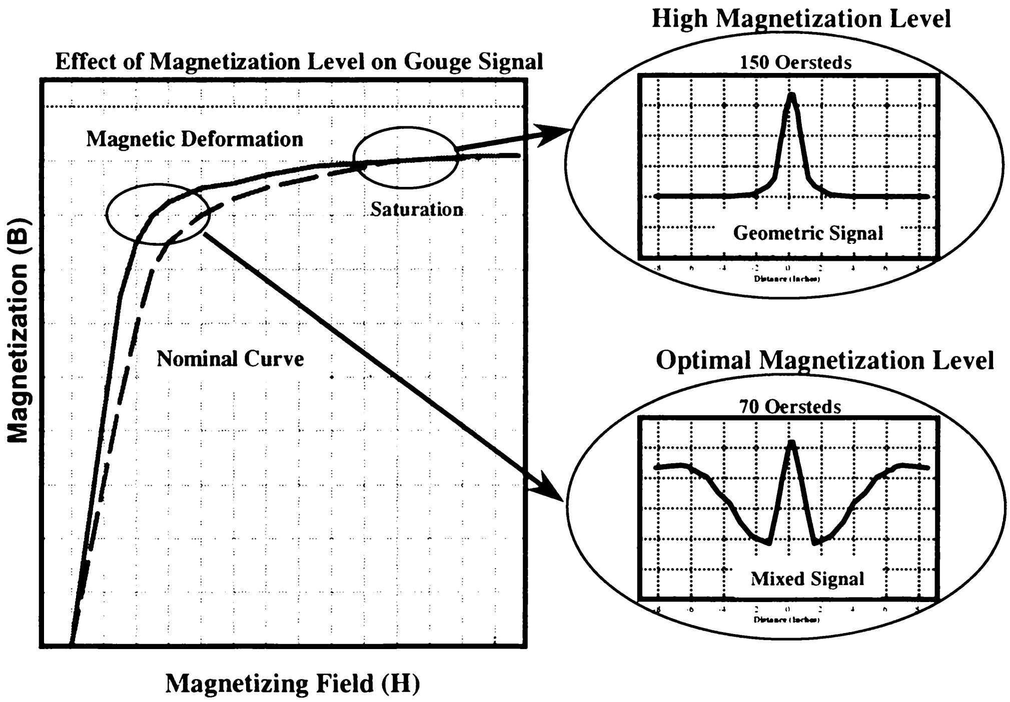

Figure 1. The general effect of magnetic deformation on the B-H curve and its effect on the MFL signal.

magnetization level, where the effects of magnetic deformation disappear, the signal contains information on only the geometric deformation. Figure 1 shows the magnetic deformation's effect on the B-H curve and its effect on the MFL signal for a simple gouge with removed metal.

The decoupling procedure is illustrated in Figure 2. First, the MFL signal is measured at the low magnetization level, i.e., the level at which the effects of magnetic deformation are greatest. Since geometric deformation also produces flux leakage at this magnetization level, the measured signal is a complex mixture containing information on both the geometric and magnetic deformation. Second, the MFL signal is measured at a high magnetization level. At high magnetization levels, effects of magnetic deformation vanish and the MFL signal is due to only defect geometry. Then, the high magnetization level signal (geometric signal) is "scaled down" to the lower magnetization level of the mixed MFL signal. This scaled geometric signal is the hypothetical MFL signal caused by the defect geometry at the low magnetization level. Finally, the scaled geometric signal is subtracted from mixed MFL signal. The result is the signal caused only by the magnetic deformation.

SCALING

Since only signals at the same magnetization level can be meaningfully added or subtracted, a procedure must be established to adjust one of the signals. Scaling is the process whereby the geometric signal measured at a high magnetization level is used to determine the geometric signal at the lower magnetization level. This scaled geometric signal is the hypothetical MFL signal at the lower magnetization level in the absence of

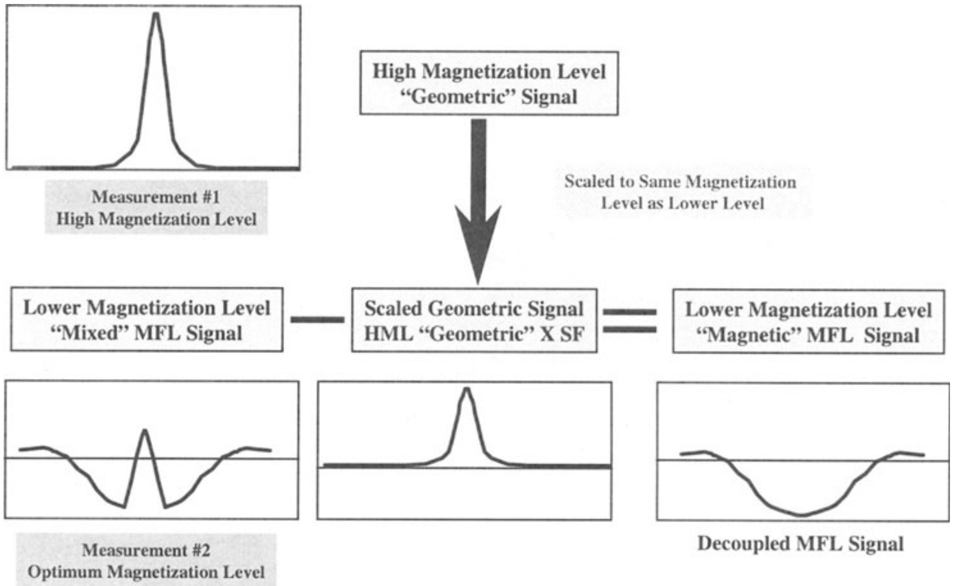

Figure 2. Illustration of the decoupling process.

magnetic deformation. Subtracting the scaled geometric signal from the mixed signal will reveal the signal caused by magnetic deformation.

Scaling requires specific knowledge of how the geometric component of an MFL signal changes with magnetization level. Generally, the signal changes its amplitude and shape. The shape change can be viewed as a nonuniform amplitude change across the signal. For example, the center of the signal may have a greater amplitude change than the ends of the signal, giving rise to the change in shape.

To simplify the scaling process, the magnetization bias is noted and removed for both the high and low signals at the beginning of the process. Sensors near the surface of the pipe wall measuring the axial component of the magnetic field provide an estimate of the bias level. The amplitude of the bias signal is proportional to the magnetization level but is dependent on sensor design variables including liftoff.

The decoupling of the flux leakage signals with the bias removed works as follows. The low magnetization level signal with the bias removed is referred to as the mixed flux leakage signal, MFL_{MIX}. The high magnetizing level signal with the bias removed is called the geometric flux leakage signal MFL_{GEOM}. The MFL_{GEOM} is translated to the lower magnetization level by a scaling function, SF. This scaled geometric signal is then subtracted from the mixed signal. The result is a signal due to the magnetic deformation only, MFL_{MAG},

$$MFL_{MAG} = MFL_{MIX} - SF \times MFL_{GEOM} \quad (1)$$

This signal is referred to as the decoupled signal. This signal is most important since it will reveal the presence of gouging.

The Scaling Function

The equivalent geometric signal at low magnetization signal, MFL_{EQG}, is given by

$$MFL_{EQG}(x,y) = SF(x,y) \times MFL_{GEOM}(x,y) \quad (2)$$

where x and y are the spatial coordinates of each signal. The coordinate references can be important. If the shape of the signal changes with magnetization, each two-dimensional spatial coordinate of the signal must be scaled differently. If the shape of the signal does not change, the entire signal is equally scaled. In this case, the scaling function is independent of the coordinates and becomes a simple scalar function.

The bias level must be measured to determine magnetization level, and it must be subtracted out of the geometric signal before the resultant signal is multiplied by the scaling function to give the scaled geometric signal without bias. The scaled geometric signal without bias is subtracted from the measured mixed MFL signal without bias to yield the decoupled signal.

Determining the Scaling Function

Previous experience [3–4] suggests that the scaling function is dependent on the magnetization level, defect geometry, and tool design. At lower magnetization levels, the geometric component of the MFL signal cannot be directly measured as a function of these parameters. However, finite element modeling techniques work well for parameter isolation and were used to study these variables. Accordingly, 20 mechanical damage defect geometries were modeled and their geometric signals computed as a function of magnetization level. These 20 geometries included dents, gouges, and dents with gouges. The dent depths ranged from 1/8 to 1 inch deep, gouge depths ranged from 1 to 10 percent of wall thickness, and defect lengths/widths ranged from 1.0 to 6.0 inches.

Based on the modeling results, the scaling function for each coordinate can be written as:

$$SF(x,y) = F_1(ML) + F_2(DD) + F_3(OGF) + F_4(OV) \quad (3)$$

where SF(x,y) is the scaling function at spatial coordinate (x,y), F_n is a Function of n^{th} order importance; ML = Magnetization Level; DD = Defect Depth; OGF = Other Geometric Factors (e.g., Length, Width); and OV = Other Variables (e.g., Sensor Design, Magnetizer Velocity). Note that each F_n may be spatially dependent.

Approximating the Scaling Function

The exact scaling function is a two-dimensional function dependent on many parameters. Determining the exact scaling function given the limited modeling set is difficult. Therefore, for this project, the scaling function was approximated. Two approximations were made.

The first approximation is that the scaling function is independent of a signal's spatial coordinates. For the geometries studied, the results showed that the signal shape does not appreciably change as a function of magnetization level. This fact implies that the amplitude scaling is roughly uniform over the whole signal. Therefore, the two-dimensional scaling function can be approximated by a scalar function. The success of this approximation depends on the geometry of the defect. Experiments have shown that for dent depths less than 0.75 inch and gouges less than 10 percent deep, this approximation is very good while performance degrades for dent depths between 0.75 and 1.00 inch deep and gouges up to 20 percent deep. It becomes less exact for deeper dents and gouges. This phase of work assumed that the scaling function is a scalar quantity.

The second approximation is to ignore all variables except magnetization level. To a first order, the scaling function primarily depends on the level from and the level to which the signals are being scaled. Figure 3 shows the scaling function as a function of the magnetizing level for the variety of defects. All signals were scaled to a magnetizing force of 70 Oersteds. The solid line represents this "best fit" for its dependence on magnetization.

With these approximations, the scaling function can be written as a scalar dependent only on the magnetization levels:

$$SF(LML, HML) \approx A(LML)e^{-\alpha(LML)\,\mathrm{HML}} \tag{4}$$

where LML and HML refer to low and high magnetization levels, respectively.

The terms A and α are functions of the low magnetization level. Figure 4 shows the scaling function for high magnetization levels of 138 and 150 Oe and lower magnetization levels between 50 and 70 Oe. Referencing Figure 4, to scale from 150 Oe to 70 Oe, the scaling function is approximately 0.465. This graph can be used to approximate the scaling function for most cases.

EXPERIMENTAL RESULTS

The purpose for using multiple magnetization levels and decoupling the signals is to expose the magnetic deformation. The magnetic component of the MFL signal is caused by permeability changes in the pipe material. The magnetic deformation is caused by the interaction of residual stress, plastic deformation, and cold work resulting from the mechanical damage on the magnetic domains of the material. The relationship between these parameters and the magnetic deformation is very complex. Extracting precise measurement of material properties is made more difficult by the fact that flux leakage is related to the magnitude of the change in permeability and also the volume of material affected. Therefore, fully characterizing the magnetic deformation in a pipeline and determining mechanical properties may not be possible using this flux leakage technique. However, the decoupled magnetic component does provide useful information. Each defect type, e.g., a gouge, has a similar residual stress and plastic deformation pattern, yielding a similar magnetic deformation signature.

Thirty-eight dents with varying depth, length, and extent of gouging have been examined. Figure 5 shows the low and high magnetization and the decoupled image of a 0.75 inch deep (3 percent of diameter), 6 inch long dent with a 0.014 inch deep (5 percent of wall thickness) gouge. The magnetic component shows that the true extent of the damage is outside the immediate defect area. Residual stress and plastic deformation extend outside the immediate area of the defect and produce magnetic deformation that is detectable.

Analytical and experimental work has shown that important information can be obtained from the magnetic component of the signal. For example, the load used to create

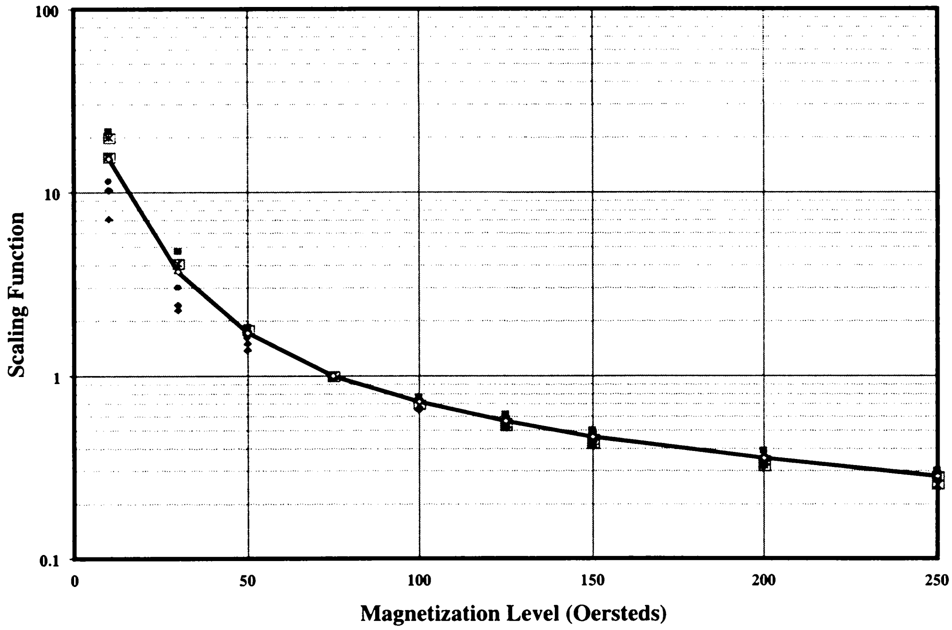

Figure 3. Scaling as a function of the magnetizing level.

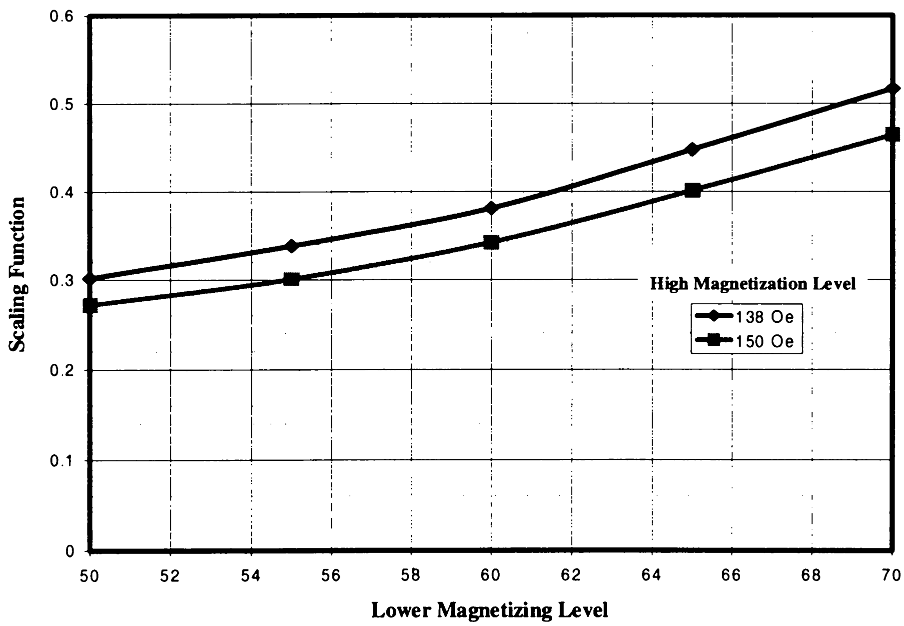

Figure 4. The approximated scaling function.

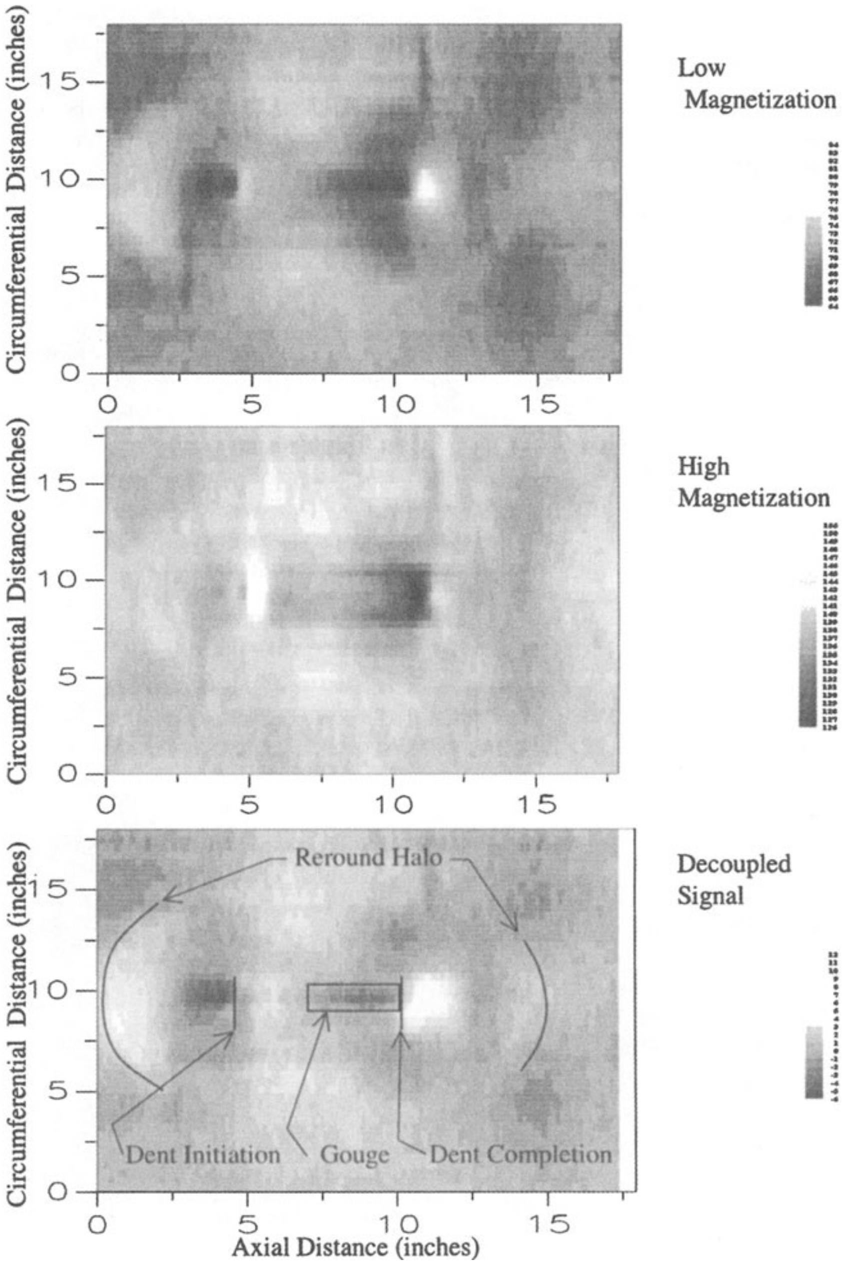

Figure 5. Decoupling of a 0.75 inch deep (3 percent of diameter), 6 inch long dent with a 0.014 inch deep (5 percent of wall thickness) gouge.

the defect is related to the peak-to-peak amplitude of the decoupled signal. The decoupled signal amplitude is also a function of pipe material, indentor geometry, and pipeline pressure under which the defect was made. After denting, the pipeline will reround due to internal pressure. Even when a dent at formation is quite large, the residual dent may be very small. Knowledge of the maximum dent depth at formation is useful in modeling mechanical damage severity. Measurement of dent depth using mechanical caliper tools can only give only the residual depth. Test data show that information on maximum dent depth can be detected in the decoupled image, and is referred to in Figure 5 as the reround halo. The halo is a flux leakage signal that surrounds a defect produced by the changes in magnetic property in the rerounding zone.

CONCLUSIONS

Flux leakage from mechanical damage defects is caused by geometric and magnetic changes. The geometric part of the flux leakage signal is caused by denting, metal loss, and wall thinning. The magnetic part of the flux leakage signal is caused by cold work, plastic deformation, and residual stress. At high magnetization levels, the MFL signal is due mostly to defect geometry. At lower magnetization levels, the MFL signal is caused by both the geometric and magnetic deformation. If the geometric MFL signal obtained at higher magnetization levels can be scaled and subtracted from the mixed MFL signal obtained at a lower magnetization level, the magnetic MFL signal will be apparent. In this way, the MFL signal can be decoupled into its geometric and magnetic components. The scaling of the higher magnetization level signals is possible, and multiple magnetization levels provide unique information about the nature of mechanical damage defects.

ACKNOWLEDGMENTS

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