Development of a differential test device for eddy current rail inspection

Marcelo Gutierrez[1,3], Javier O Fava[1,2], Tomas A Di Fiore[1], Marta C Ruch[2], Rodrigo Romero[1,2] and Juan Vorobioff[2,3]

1 Facultad Regional Haedo, UTN, Argentina, mgutierrez@frh.utn.edu.ar
2 Comision Nacional de Energia Atomica, Argentina
3 Facultad Regional Buenos Aires, UTN, Argentina

Abstract

The renewal of railway infrastructure currently underway is promoting, at a local level, an upgrading of the systems for non-destructive rail inspection, be it prompted by requirements of the new rolling material or for the sake of better and safer operating conditions. Conventional ultrasound has been historically the non-destructive testing (NDT) method most widely used for rail inspection. However, this method is not suitable for the detection of surface flaws, such as the contact fatigue flaws on the running surface (head checks); these surface flaws can be detected by eddy currents (1). Within this framework we are developing a prototype system for the eddy current inspection of railways. The system uses the near-field send-receive technique in order to inspect planar components of ferromagnetic steels. The inspection head consists of three bobbin coils, the sender in the centre, receivers at both sides, connected in differential mode. The displacement of the inspection head is made by an X-Y positioning device.
Different coils were used in the present work; results from the scan of flat samples of carbon steel with calibrated grooves and of actual rail pieces are presented. Bridge output signals were acquired and processed with a lock-in algorithm in order to get relevant information of the inspected grooves. The influence of lift-off on the groove signals was also studied, with an aim at finding some analysis algorithm which would minimize the influence of lift-off in the case of in-service inspection.

1. Introduction

Railway tracks are submitted to large flexural and shear stresses, plastic deformation and wear, which degrades their structural health and may derive in one of the main causes of railway accidents: track failure due to the propagation of surface defects on the rolling head. These surface defects are generated by the interaction between wheel and track by a mechanism known as rolling contact fatigue (RCF)), (1) (2). Most of in-service failures were earlier caused by the propagation of internal defects in the rail web or head (from the manufacturing process) or by fatigue or excessive wear. However, the introduction of cleaner manufacturing processes have reduced the amount of internal defects and the use of wear resistant high carbon steels and of hardening treatments on the head surface rails resulted in a reduction of failure due to wear. As a consequence, failure mechanisms related to the propagation of surface defects produced by RCF are now a highly common cause of railway track failures.

In the context of in-service NDT of railway tracks, it is important to develop techniques for locating and evaluating defects which require very low service interruption. At present, in our medium, ultrasonic testing (UT) using trolleys is the only technique currently used for railway track inspection (an example of which can be found in (3)). A major shortcoming of this technique is its rather low speed, the trolley being pushed by a person. This conventional UT technique is used to inspect welds on tracks and to detect cracks penetrating the rail head or with a considerable size in the web or foot, i.e. internal and/or volumetric defects (penetration within the material greater than 4-5 mm, approximately). UT detection of surface cracks smaller than 4 mm is a rather difficult task, even in laboratory conditions and/or at low speeds (5-10 km/h). Although some high speed UT techniques have been developed (4) (5), they are optimized for volumetric defects. Besides, inspection speed is also limited by sound propagation velocity in the material and surface condition of the rail – a couplant medium (normally water) is necessary. In references (4) and (5) a combination of UT and eddy currents testing (ET) is presented. ET is mainly used for the early detection of RCF type surface defects and the evaluation of their growth. This cannot be achieved with UT, which nevertheless constitutes a very powerful method for the detection of other types of defects (4).

One of the objectives of the present work is the innovation in ET-NDT techniques for the inspection of railway tracks and of flat ferromagnetic components. Emphasis is put in ET signal processing and analysis, with the intention of identifying defects, evaluating the damage they pose and following their evolution. Locally, this work might contribute to the inspection of railway tracks, creating knowledge for the development of inspection systems mounted on trains, offering real-time signal processing and reducing inspection time.

2. Material and methods

2.1 Alternate current bridge and signals

The send-receive near-field differential ET technique was used to detect the distortion of the eddy current flow produced by defects. An inspection head with three cylindrical coils was constructed: the sending coil (emitter) in the central position, the two reception coils (receivers) symmetrically located and connected in the differential mode. The variable magnetic field is generated by a sinusoidal wave V_{ref} through the emitter L_e, figure 1. The electronic circuit feeding the emitter is a voltage controlled current source which supplies current of known intensities. The receive coils L_1 and L_2 are connected to two branches of an alternate current bridge (AC); voltage variations V_{L1} and V_{L2} are recorded during the scans. The two variable impedances Z_1 and Z_2 in the other two branches, figure 1, are used to balance the bridge to a nearly zero differential voltage, V_{dif}, in a defect free region. The value of the voltage V_{dif} will change when the coils reach a heterogeneous region. Because the values V_{dif} in the presence of a defect are small, a differential amplifier is necessary, in order to extract the defect indication.
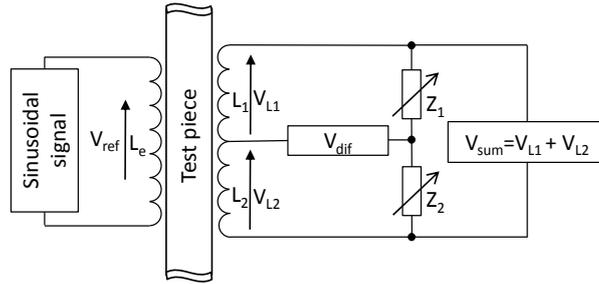
Figure 1. AC bridge in the ET equipment. Differential mode send/receive technique.

The value V_{dif} depends on lift-off; variations of the latter during the tests will affect the correct characterization of the defects. In the particular head-design with the receivers connected in the differential mode, the bridge balance will not be affected by homogeneous changes in lift-off under all the inspection-head. But the amplitude V_{dif} will be affected in the vicinity of a discontinuity. The effects produced on V_{dif} by those changes in lift-off can be evaluated and compensated for using the amplified voltage $V_{sum} = V_{L1} + V_{L2}$ (see figure 1). V_{sum} is a compensation parameter, by means of which the amplitude V_{dif} may be correctly restoreed in places where there is a variation in lift-off.

Moreover if the circuit is near external sources of electrical noise, the quality of V_{dif} and V_{sum} will decrease. Hence the unwanted noise should be filtered out. If an analogical filter is implemented, it must have a very narrow bandwidth (BW) (6). This option implies a very high $Q = Fd/BW$, with Fd: frequency of the desired signal and BW: bandwidth. The output from the AC bridge is fed into a digital lock-in amplifier, highly selective in the recovery of the wanted frequencies in an environment with high electrical noise (6). The discrete signals $X_{sum}[n]$, $X_{dif}[n]$ and $X_{ref}[n]$ in figure 2 are the digitized version of the analogical signals V_{sum}, V_{dif} y V_{ref}, respectively.
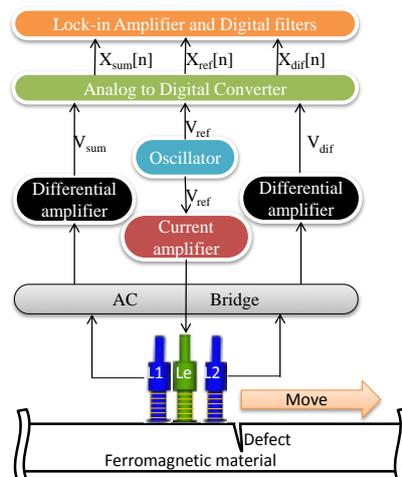
Figure 2. Block diagram of the inspection and data handling system

The signals $X_{sum}[n]$ and $X_{dif}[n]$ are demodulated with an algorithm implemented in the lock-in amplifier, where two signals are multiplied, the output is processed by a digital low pass filter (LPF) using an infinite impulse response (IIR), and the demodulated signal X is obtained. The digital LPF is a second order Butterworth of unit gain in the pass band and cutoff frequency of 10 Hz, to recover the DC component of the digital lock-in amplifier.

2.2 Coil design

Tests were made with cylindrical coils wound on plastic ABS cores with inner radius 4 mm, lift-off 0.4 mm and height 15 mm with a different number of turns: 400, 600 and 800 of copper wire AWG36 (0.127 mm). The highest output sensitivity of the system was achieved with the 400-turn inductor.

2.3 Calibration pieces

In order to study the electrical transient response of the system to cracks, a flat calibration piece was constructed on a 75 mm wide slab of ferromagnetic SAE 1010 steel. The size of the artificial cracks in this calibration piece is detailed in table 1.

Table 1. Cracks in the SAE 1010 flat calibration piece.

|	Crack 1	Crack 2	Crack 3	Crack 4
Depth (mm)	3.0	2.0	1.0	0.5
Width (mm)	0.3	0.3	0.3	0.3

Additionally another calibration sample was constructed on a piece of a railway track (SAE 1566). It contains 4 cracks separated 40 mm, two of them perpendicular and two oblique to the piece axis, as described in table 2.

Table2. Cracks in the railway track section calibration piece (SAE 1566 steel).

	Crack 1 (α=45º)	Crack 2 (α=60º)	Crack 3 (α=90º)	Crack 4 (α=90º)
Depth (mm)	2.0	2.0	3.0	1.0
Width (mm)	0.3	0.3	0.3	0.3

2.4 Experimental set up

An X-Y positioner was constructed for sensor movement and control, with a minimum displacement of about 0.01 mm. The inductors were correctly coupled to the calibration pieces with a specially designed spring loaded coil holder, which helped reducing lift-off effects (figure 3). An electronic circuit was designed to control the input current fed to L_e by a signal generator, to adjust the balance of the AC bridge and to adequate the voltages V_{sum} and V_{dif}. These signals, together with V_{ref} were sampled with a 16-Bit data acquisition device with a sample rate of 1 MHz.
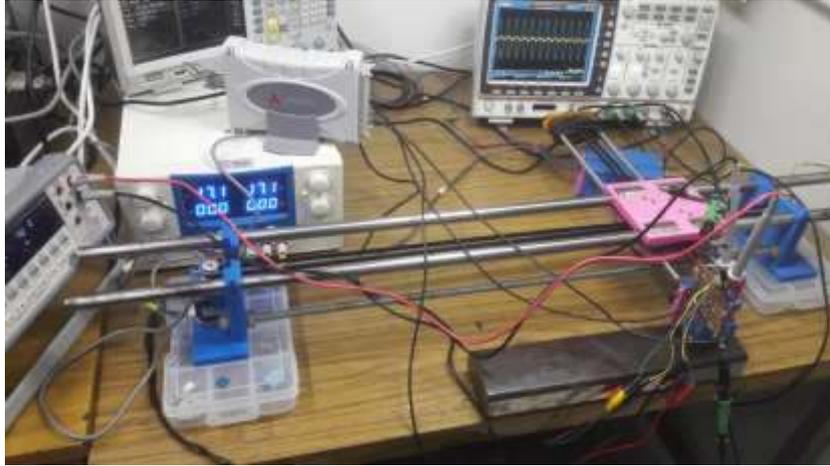
Figure 3. Experimental set up for the ET inspection.

3. Results

3.1 Scans on the flat SAE 1010 calibration piece and lift-off compensation

Scans were made on the SAE 1010 calibration piece described in table 1, with different lift-off values, identified as d, which was varied from the intrinsic coil lift-off (0.4 mm) up to 6.4 mm, at 1 mm steps. When d is increased, the amplitude of the wave associated to each defect is reduced (X component of the digital lock-in amplifier signal); for a frequency of 24 kHz, the results are shown in figure 4 (a).
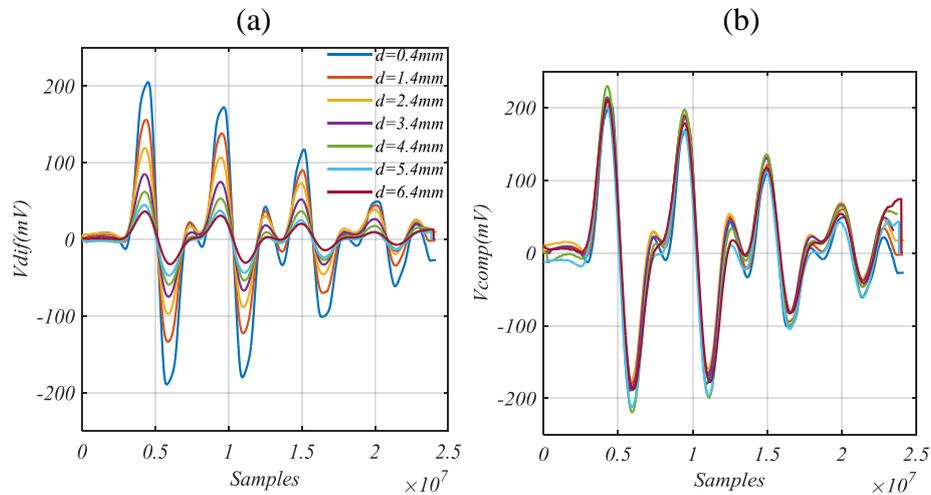
Figure 4. (a) X component of the digital lock-in amplifier after processing the V_{dif} signal at different lift-off–calibration piece distances. (b) Compensated V_{dif} for different lift-off variation. SAE 1010.

The signal V_{sum} of the AC bridge in figure 1 was used to compensate the effect of the lift-off variation. To construct the lift-off compensation function; first, the peak values of V_{sum} on a defect-free portion of the SAE 1010 calibration piece were measured at different lift-off (d) conditions, (table 3).

Table 3. Relationship between V$_{sum}$ and lift-off.

Lift-off (d) (mm)	V$_{sum}$ (V)
0.4	3.190
1.4	3.045
2.4	2.949
3.4	2.886
4.4	2.844
5.4	2.816
6.4	2.797

Second, the peak values V_{dif} of the crack 1 signal were measured as a function of lift-off (first peaks in figure 4 (a)); these V_{dif} were evaluated from the measured signal. Then with the aforementioned peaks values of V_{sum} and V_{dif}, a compensation function was calculated. This compensation function is the fitting function between the ad hoc coefficient (k_{comp}) defined in formula (1) and V_{sum}.

$$k_{comp}(d) = \frac{\text{Peak Amplitude } V_{dif}(0.4 \text{ mm})}{\text{Peak Amplitude } V_{dif}(d)} \qquad (1)$$

This fitting function was of the type: $y = y_0 + A \cdot \exp(R_0 \cdot x)$, were $y = k_{comp}$ and $x = V_{sum}$. The values of the parameters of the adjusted curve are presented in table 4.

Table 4. Parameters of the non-lineal fit

| y_0	A	R_0	R^2
1.11±0.09	(1.0±0.3)x10^{18}	-14±1	0.996

In an analogous way, by applying the compensation coefficient to the lift-off reduced signals of the other defects (figure 4 (a)) the V_{dif} signals may be restoreed, monitoring V_{sum} during the inspection. The procedure is as follows: the amplitude reduced signal is scaled with k_{comp} using equation (2); so the restoreed signals in figure 4 (b) are obtained.

$$V_{comp} = k_{comp} \cdot V_{dif} \qquad (2)$$

3.2 Scan of the railway track calibration piece

To show the detection power with the lineal differential set up constructed here, the railway track section calibration piece (table 2) was tested. Results are presented in figure 5. Amplitude of V_{dif} for cracks 1, 2, 3 and 4 from left to right are shown. All 4 cracks were detected. The amplitudes might indicate lack of material (surface is not planar). Cracks 1 and 2 have the same depth and are skewed. Crack 2 is at an angle of 60º to the axis, being more perpendicular to the scan; hence a larger amplitude might be expected compared to crack 1.

More analysis should be made in the future to analyze phase and width of the signals, in order to get more parameters to identify damage and defect orientation.
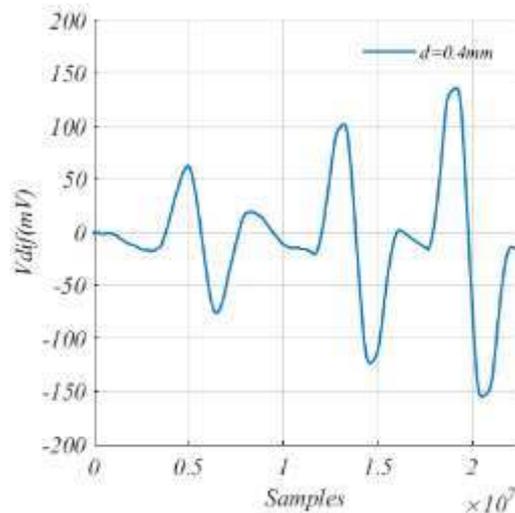
Figure 5. Amplitude of V$_{dif}$ for cracks 1, 2, 3 and 4 from left to right. Test of the railway track section calibration piece (SAE 1566).

4. Conclusiones

An ET prototype equipment was designed, manufactured and tested; the main goal is the inspection of flat ferromagnetic components and railway rails. The near field send-receiver technique was used, and it was optimized to inspect ferromagnetic steels.

An inspection head with three cylindrical coils was constructed: the sending coil (emitter) in the central position, the two reception coils (receivers) symmetrically located and connected in the differential mode.

It was possible to identify signals coming from cracks with depths between 0.5 mm and 3 mm. The experimental arrangement could be configured to inspect a flat calibration standard with grooves in ferromagnetic steel, and another sample made on a piece of rail.

A lift-off compensation method was tested in the scanning of the flat calibration piece. It was possible to restore the signals diminishing for the lift-off effect, by means of a compensation function. In the future this method could be studied to be applied during a railway tracks inspection.

A digital lock-in amplifier algorithm was developed, which allowed obtaining the signals defects. This algorithm avoided designing an analog electronic circuit that fulfills the same function, reducing the dimensions of the printed circuit designed.

As future jobs it can be listed: new coil designs and arrangements, include width and phase analysis of the signals and test the lift-off compensation method over a rail track standard with a positioner that can simulate lift-off variation effects.

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