

APPLICATION OF THE NONLINEAR HARMONICS METHOD TO CONTINUOUS
MEASUREMENT OF STRESS IN RAILROAD RAIL

G.L. Burkhardt and H. Kwun

Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78284

INTRODUCTION

The buildup of thermally induced compressive stress in continuously welded railroad rail [1,2] can result in track buckling (lateral displacement of the track over a distance of approximately 100 feet [3]) which can cause derailment of a passing train. Therefore, a direct stress measurement approach utilizing a probe which could be scanned continuously along the rail would be very valuable for surveying the state of rail stress to determine if a potentially unsafe condition exists. In the research described in this paper, the nonlinear harmonics (NLH) method was investigated as an approach for measuring stress in a railroad rail. Laboratory measurements were taken while the probe was scanned along the web of a 3-foot-long section of rail subjected to compressive stress in a loading machine. Approaches for reducing the effect of material property variations by using stress-induced anisotropy and spatial averaging of the data were also investigated and shown to be very promising.

BACKGROUND

The application of a sinusoidal magnetic field to a ferromagnetic material results in the generation of odd-numbered harmonic frequencies in the magnetic induction. This is because the relationship between the applied field and the induction is nonlinear [4,5], as determined from the shape of a magnetic hysteresis loop. The amount of the harmonic content is dependent on the hysteresis loop characteristics.

The characteristics of hysteresis loops are affected by the state of mechanical stress in the material through magnetoelastic coupling [6-9]. Therefore, the harmonic content of the magnetic induction is also influenced by stress, and the stress dependence of the harmonic frequencies can be used as a means for measuring stress [10-14].

The hysteresis loops, however, are also affected by other material characteristics such as chemical composition, microstructure, and hardness [7]. Since variations in these properties could affect the accuracy of stress measurement, it is important to minimize their influence. One approach, which was investigated in this research for measuring stress and

reducing the effect of material properties not related to stress, was stress-induced anisotropy of the third harmonic amplitude. Stress-induced anisotropy is defined as:

$$S = (A_{\text{parallel}} - A_{\text{perp.}}) / (A_{\text{parallel}} + A_{\text{perp.}}) / 2 \quad (1)$$

where S is the stress-induced anisotropy and A_{parallel} and $A_{\text{perp.}}$ are the amplitudes of the third harmonic with the magnetic field applied parallel and perpendicular to the stress direction, respectively. For materials with positive magnetostriction, A_{parallel} increases with tension and decreases with compression; $A_{\text{perp.}}$ exhibits the opposite behavior [11,15]. In the absence of stress, S is approximately zero, even if the material properties vary [15]. S becomes positive with tension and negative with compression.

An additional approach for reducing the effect of localized material conditions on the stress measurement was spatial averaging. In the case of railroad rails (and possibly other large structures), trends in the stress over a relatively large distance are more important than the stress at a given point. Therefore, a spatial averaging technique can be used to smooth the localized variations obtained when making numerous measurements as a probe is being scanned over a large area. Spatial averaging is accomplished by replacing the measurement at each discrete location by the average of the measurements obtained within a specific distance on each side of the location.

EXPERIMENTAL ARRANGEMENT

A schematic diagram of the NLH probe is shown in Fig. 1. The probe consisted of an excitation coil to generate a magnetizing field and an adjacent sensing coil to sense the magnetic induction in the specimen.

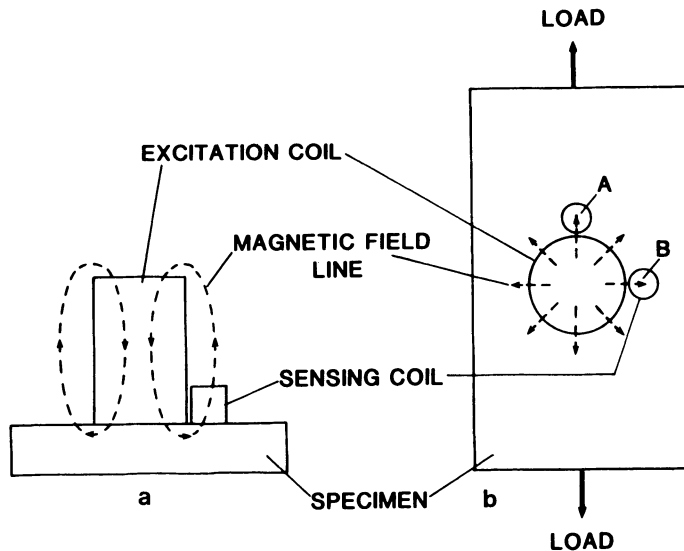


Fig. 1. Schematic diagram of the nonlinear harmonics probe and magnetic field line distribution: (a) side view and (b) top view. The sensing coil in positions A and B detects the magnetic induction parallel and perpendicular to the loading direction, respectively.

Both coils were oriented with their axes perpendicular to the surface of the specimen. The excitation coil dimensions were 0.74 in. high X 0.59 in. outside diameter (OD), and the coil was wound on a 0.25-in. dia. ferrite core. The dimensions of the sensor coil were 0.186 in. high X 0.25 in. OD.

The probe could be oriented with the sensor at either position A or B as shown in Fig. 1b. Figure 1a shows the side view of the path of the applied magnetic field produced by the excitation coil, and Fig. 1b shows a top view indicating that the field is radially distributed in the specimen. Therefore, with the probe oriented with the sensor at location A, the sensor detects the magnetic field component which is parallel to the applied stress direction; and with the sensor at location B, the perpendicular field component is detected. These two probe orientations were used to make the anisotropy measurements with the magnetic field oriented both parallel and perpendicular to the stress direction. The probe is shown positioned on the railroad rail specimen in Fig. 2.

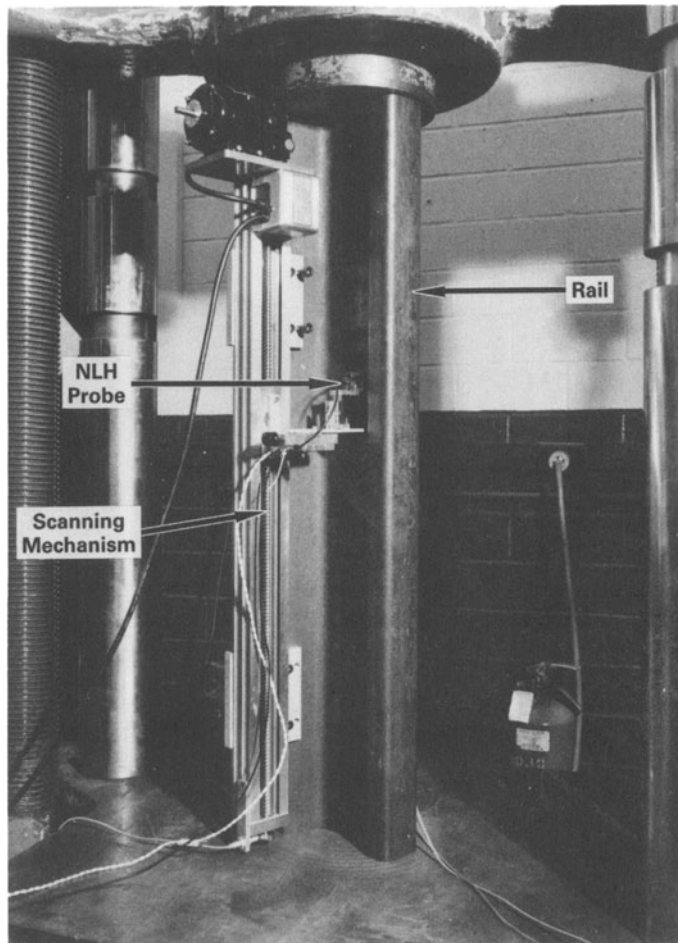


Fig. 2. Railroad rail in the loading machine with the nonlinear harmonics probe configured for scanning the web of the rail specimen.

A block diagram of the instrumentation is shown in Fig. 3. The computer was used both to control the function generator and to record and analyze the data. The function generator provided a 10-kHz sine wave to the power amplifier used to drive the excitation coil in the probe. The signal from the sensing coil was input to a preamplifier and then to a notch filter to reduce the amplitude of the signal component at the fundamental frequency. The resulting signal was then amplified and fed to a signal analyzer to digitize the signal and compute the frequency content by means of a Fast Fourier Transform. The data were transferred to a computer for analysis.

The specimen consisted of a section of 119-lb (terminology for the weight per yard) used railroad rail approximately 3 ft. in length. The rail was positioned in a 200,000-lb. capacity loading machine for application of compressive stress, as shown in Fig. 2. A motor-driven slide mechanism was used to scan the probe along the web of the rail over a distance of 2 ft. at a velocity of 0.5 in./sec. An encoder attached to this mechanism controlled the data acquisition so that data were sampled at known probe locations in 0.5-in. increments along the rail. The probe was spring loaded against the surface of the rail.

EXPERIMENTAL RESULTS

NLH data were taken as the probe was scanned along the web of the rail with the probe oriented with the magnetic field direction parallel to the direction of stress and then perpendicular to the stress direction. Data from the parallel probe orientation are shown in Fig. 4. In this figure, the amplitude of the third harmonic is plotted as a function of

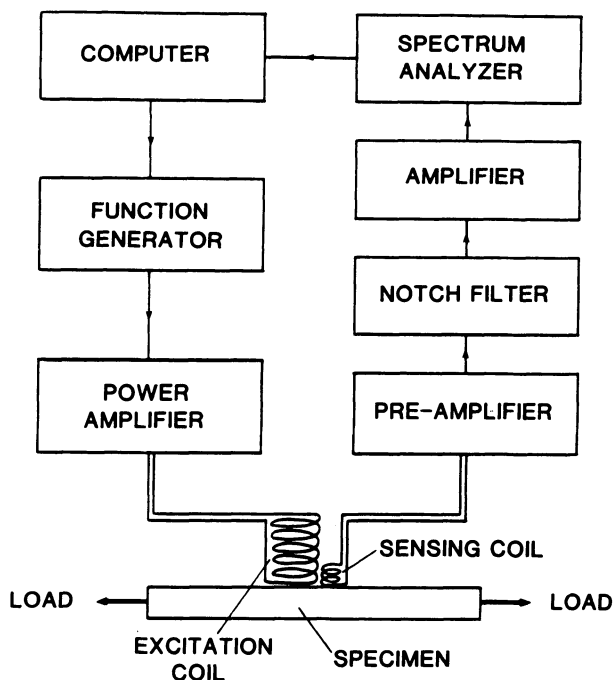


Fig. 3. Block diagram of NLH instrumentation.

position along the length of the rail for zero applied stress and for 8.6- and 17.2-ksi compression. The signal amplitude generally decreases with increasing compression; however, a considerable amount of fluctuation exists in the signal amplitude for each stress level at different positions along the rail. Although the cause of these variations was not investigated, they were attributed to localized differences in residual stress, material composition, and material condition (i.e. hardness). The data at -8.6 ksi are generally discernible from those at 0 stress; however, it is difficult to distinguish the -8.6 and -17.2 ksi data from each other because of the localized fluctuations in the data.

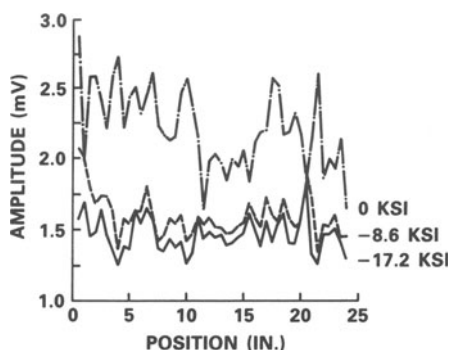


Fig. 4. NLH signal amplitude vs. position along the rail with the magnetic field direction parallel to the applied stress direction.

Experimental data taken with the magnetic field direction perpendicular to the applied stress direction are shown in Fig. 5. As expected, the signal level increases with increasing compression. Again, it is difficult to distinguish the -8.6 and -17.2 ksi data because of the localized variation in the signal amplitude.

The stress-induced anisotropy was computed from the parallel and perpendicular data using equation 1. The anisotropy is plotted as a function of position along the rail in Fig. 6. Although localized variations in the anisotropy exist, the degree of variation is not as great with respect to the changes caused by stress with the parallel or perpendicular data. Therefore, the changes caused by stress are more readily distinguished.

The anisotropy data were then processed using the spatial averaging technique where each measurement was replaced by the average of the measurements within a distance of 1 in. on each side. The results are shown in Fig. 7. The spatial averaging removes most of the localized fluctuations, resulting in a much smoother signal. The three stress conditions are now readily distinguished from each other.

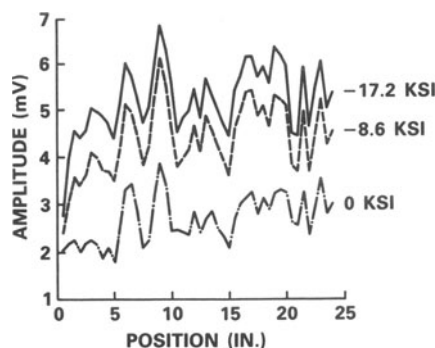


Fig. 5. NLH signal amplitude vs. position along the rail with the magnetic field direction perpendicular to the applied stress direction.

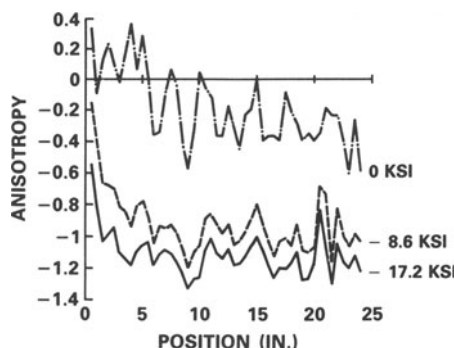


Fig. 6. Anisotropy in the NLH signal vs. position along the rail.

For application to an actual railroad track structure, the averaging would be performed over a distance of several feet, which would further reduce the effects of localized variations. Although the maximum probe scanning speed is not known at this time, there appears to be no fundamental limitation on increasing the scanning speed to approximately 10 miles/hr for measurements from a moving vehicle.

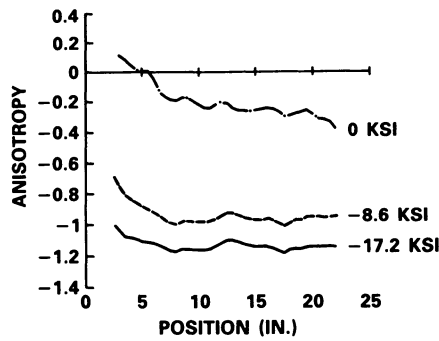


Fig. 7. Anisotropy in the NLH signal vs. position along the rail after spatial averaging.

CONCLUSIONS

1. The nonlinear harmonics (NLH) method is a sensitive means of measuring stress in railroad rail.
2. The state of stress can be surveyed rapidly by scanning a probe along the web of the rail.
3. Stress-induced anisotropy and spatial averaging reduce the effect of localized material variations on the stress measurement.

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