

MEASUREMENT OF LONGITUDINAL STRESS IN RAILROAD RAIL UNDER FIELD
CONDITIONS USING NONLINEAR HARMONICS

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INTRODUCTION

Track buckling in continuously welded rail is a significant problem in the railroad industry [1-3]. Buckling is caused by the buildup of compressive stress (longitudinal force), which is primarily caused by an increase in rail temperature while the rail is constrained and cannot expand longitudinally. The buckling is typically manifested in the wavy lateral displacement of the track over a distance of approximately 100 feet [3]. Because buckling can cause the derailment of a passing train, extensive efforts are spent on preventive maintenance of the track. If a region of rail is known to be in a high state of compressive stress, the rail can be de-stressed by cutting it, allowing it to expand, and then welding it back together. Currently, one of the major difficulties in preventing track buckling is lack of a means for detecting the highly stressed areas.

Finding techniques to reduce the incidence of buckled track can lead to improved railroad safety and profitability. During the five-year period from 1984 to 1988, Burlington Northern Railroad (BN) spent over \$25 million repairing equipment and track as a result of derailments due to buckled track. Liability claims for personal injury and damage to property not owned by BN are not included in this figure. Thus, the total cost borne by BN due to track buckling could be much larger than \$5 million per year. In addition, buckled track can lead to events that result in significant negative publicity. For example, on August 5, 1988, an Amtrak train traversing BN tracks in Montana derailed as a result of buckled track. Fortunately, there were no fatalities; however, many Amtrak passengers and crew members were injured. Research into improved management of track buckling, then, can yield significant financial and safety gains for the railroads.

With the nonlinear harmonics (NLH) technique for stress measurement [4], a sinusoidal magnetic field, H , of a fixed frequency, f , is applied to a ferromagnetic material. The harmonic frequencies, typically the third harmonic, of the applied field frequency are then detected and related to stress. These harmonics are generated due to the distortion in the magnetic induction waveform which is caused by magnetic hysteresis and nonlinearity in the magnetization curve of the material.

For structural steels with positive magnetostriction [4], the harmonic amplitude increases with increasing tension and decreases with increasing compression when the applied magnetic field is parallel to the stress, as illustrated in Fig. 1. When the applied field is perpendicular to the stress, the harmonic amplitude exhibits the opposite stress dependence.

Because of the dependence of the harmonic amplitude on the relative orientation between the stress and the applied magnetic field, the harmonic amplitude exhibits anisotropy when the material is subjected to stress. An anisotropy parameter defined as

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

where A_{\parallel} and A_{\perp} are the harmonic amplitudes obtained with the applied magnetic field parallel and perpendicular to the stress direction, respectively, is used to determine the stress. As illustrated schematically in Fig. 2, for materials with positive magnetostriction, the anisotropy is positive under tension and negative under compression, and increases in magnitude with increasing stress [4]. Compared with the actual harmonic amplitude which changes significantly with variations in material properties such as texture, hardness, and heat treatment, the anisotropy is relatively insensitive to material property variations and, therefore, is a more accurate indicator of stress.

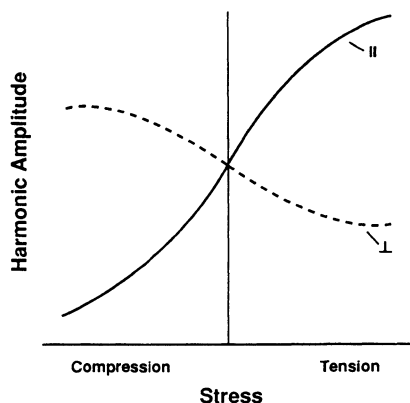


Fig. 1. Stress dependence of harmonic amplitude for materials with positive magnetostriction for applied magnetic field parallel (\parallel) and perpendicular (\perp) to stress, respectively

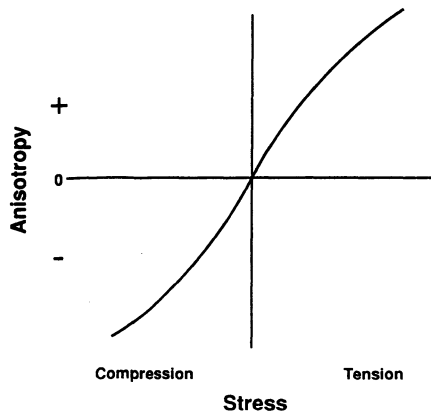


Fig. 2. Dependence of the anisotropy in harmonic amplitude on stress

APPLICATION OF THE NLH TECHNIQUE TO RAIL STRESS MEASUREMENTS UNDER FIELD CONDITIONS

Background

In a limited laboratory investigation conducted previously [5], the feasibility of measuring rail stress using the NLH method was demonstrated. The results also showed that the technique is promising as a rapid means for detecting highly stressed areas in track.

To further evaluate the practical applicability of the NLH technique, the feasibility for measuring changes in rail stress caused by temperature changes under field conditions was investigated. The following two subsections contain a description of (1) the experimental arrangement and procedures used in the field testing and (2) the results and discussions of the testing.

Field Testing Arrangements and Procedures

Field testing of the NLH technique was conducted at the Transportation Test Center (TTC) in Pueblo, Colorado, on September 28 and 29, 1988. Measurements were made on the wood-tie section of the turnaround loop at TTC. The loop was made of 136 lbs/yard weight rail (identification mark on the rail read 1360 RE CC CF & I 1974). The turnaround loop is instrumented with strain gauges and thermocouples at various locations to allow monitoring of the rail stress and temperature changes.

The instrumentation system and the probe used in the previous laboratory investigation were also used for making NLH measurements during the field testing. Detailed information on the instrumentation and probe has been given elsewhere [5].

Two test locations, approximately 50 yards apart, were selected adjacent to existing strain gauges. These locations, designated No. 1 and No. 5 in this paper, were near gauges 1C and 5C (as designated by TTC), respectively, and were on the outer side of the track. Since the strain gauges were not zero-calibrated by de-stressing the rail, the

absolute rail stress was unknown and only the relative changes in rail stress could be monitored using the strain gauges. These gauges sense strain changes in the transverse direction of the rail caused by the changes in the longitudinal force in the rail (since the rail cannot expand longitudinally, there is no apparent strain change along the longitudinal direction).

At each location, NLH measurements were made by scanning the probe over two paths which were 2 feet long and separated by approximately 1 foot. The two scan paths are designated A and B in this paper. From each scan path, NLH data were taken as the probe was scanned along the web of the rail with the probe oriented parallel to the longitudinal direction of the rail. Then the scan was repeated with the probe oriented perpendicular to the longitudinal direction of the rail. For each scan, a total of 48 data points (one for every 0.5 inch over the 2-foot scan path) were obtained; their average was calculated and later used to determine the NLH anisotropy. Averaging was done to reduce the effects of local variations in material properties on the stress measurements. While the NLH data were acquired during a scan, the corresponding rail temperature and strain gauge readings were recorded and later correlated with the NLH data.

Test Results

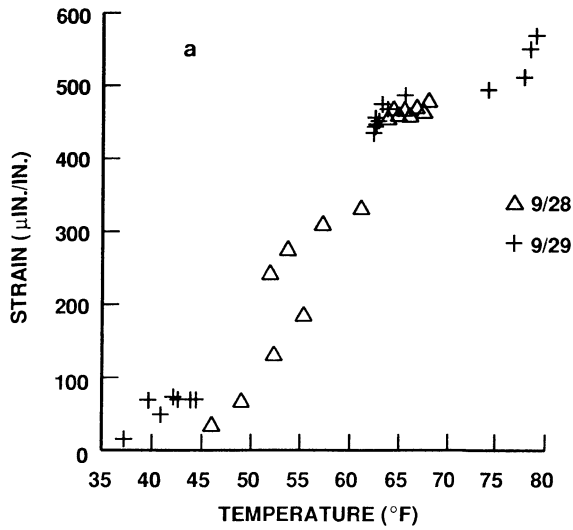
Fig. 3 shows the strain gauge readings as a function of the rail temperature recorded during the field testing. The data in Fig. 3(a) were from location No. 5, and those in Fig. 3(b) were from location No. 1. Triangle and cross symbols are for the data acquired on September 28 and 29, respectively. Since the strain gauges were not zero-calibrated, the absolute strain values indicated were of no significance; only the relative changes in their values were meaningful.

As can be seen in Fig. 3, the strain reading (transverse to the longitudinal direction of the rail) increased with increasing temperature. The strain data, therefore, indicate that the longitudinal force (or stress) in the rail is decreasing and becoming more compressive with increasing temperature. As shown, the data were somewhat scattered; for a given strain, the scatter in temperature was approximately $\pm 5^{\circ}\text{F}$.

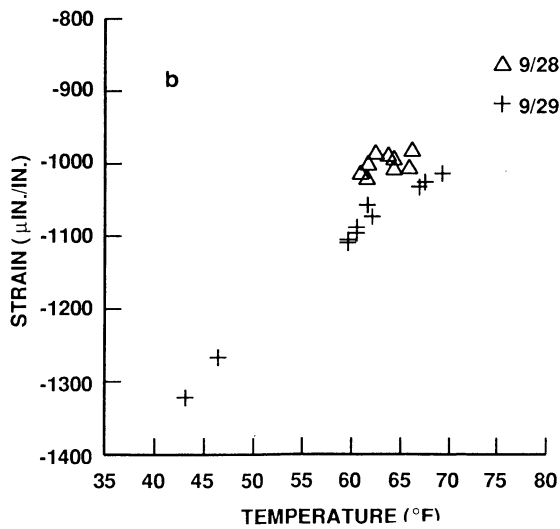
On September 28, the temperature of the rail during the testing (conducted between 7:30 A.M. and 3:00 P.M.) varied from approximately 46°F to 68°F , producing a maximum strain change of approximately 440 microinch/inch. The next day, the rail temperature during the testing (conducted between 8:00 A.M. and 3:00 P.M.) changed from approximately 37°F to 79°F , producing a maximum strain change of 546 microinch/inch. The maximum decrease in the longitudinal rail force that occurred during the two-day testing was about 84,000 lbs or 6200 psi in stress*.

The NLH anisotropy and the decrease in the longitudinal stress in the rail calculated from the strain data are shown in Fig. 4. The data in Fig. 4(a) and 4(b) were from locations No. 5 and No. 1, respectively. The triangle and cross symbols in the figure are for the data acquired from scan path A on September 28 and 29, respectively. The square and diamond symbols are for the data acquired from scan path B on September 28 and 29, respectively.

*TTC uses the equation $\text{Rail Stress} = -0.0114 \times \text{Strain}$, where strain is in microinch/inch and stress is in ksi, to convert strain change to change in the longitudinal rail stress.

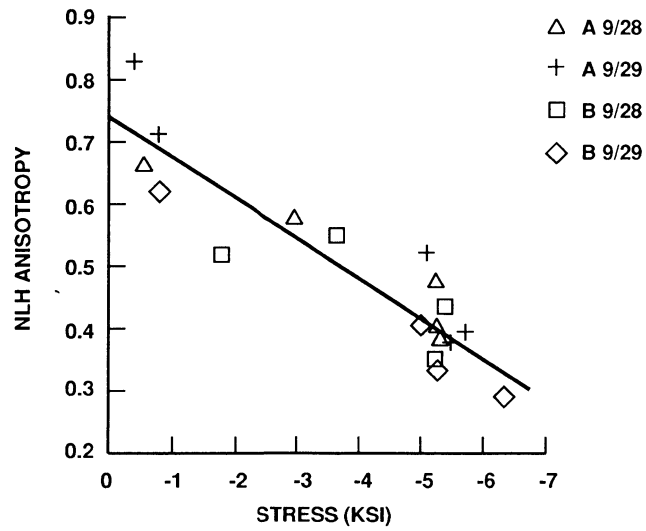


(a) Location No. 5

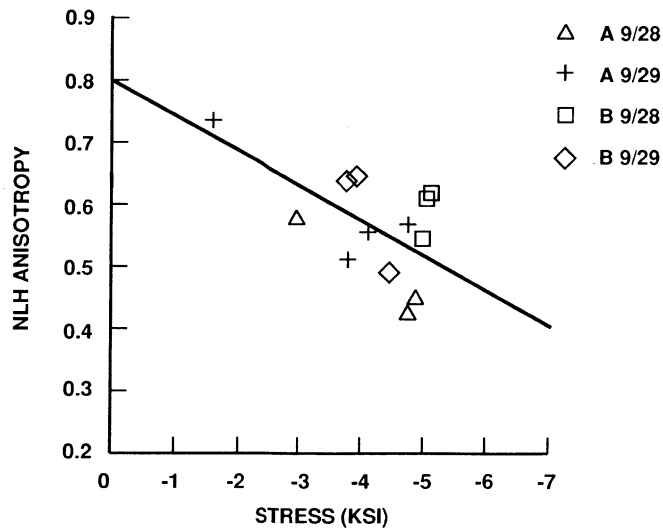


(b) Location No. 1

Fig. 3. Strain-gauge readings vs. rail temperature



(a) Location No. 5



(b) Location No. 1

Fig. 4. NLH anisotropy vs. longitudinal compressive stress

The data shown in Fig. 4 were obtained using the following procedure: (1) convert the strain to stress by using the formula given in the TTC equation, and (2) average the two stress values representing the rail forces during the NLH scan with the probe oriented parallel and perpendicular to the longitudinal direction of the rail, respectively. The second procedure was necessary because the temperature and the strain readings changed during the time the two sets of NLH data were acquired.

Additionally, the data in Fig. 4(b) were obtained by shifting the stress values to match with those in Fig. 4(a) which were determined from the strain data measured with the calibrated strain gauge. The amount of this shift was determined by overlapping the strain-temperature data in Figs. 3(a) and 3(b) and sliding the vertical axis until the data in Fig. 3(b) fell within the range of scatter of the data in Fig. 3(a). The amount of shift thus determined was +1430 microinch/inch. The validity of the shifting is based on the assumption that the longitudinal forces at locations No. 1 and No. 5 are the same. Since the strain gauges were not zero-calibrated by de-stressing the rail, the stress values shown in Fig. 4 are not absolute values but, rather, relative changes in stress values.

As can be seen in Fig. 4, the NLH anisotropy decreased with increasing longitudinal compressive stress as expected [4,5]. The data shown in Fig. 4 clearly demonstrated that changes in rail stress due to temperature can be detected using the NLH method.

The straight lines in Fig. 4 are the least-square fitted lines of the data. The slope of the line in Fig. 4(a) was approximately 0.065/ksi (1 ksi = 1000 psi). The slope of the line in Fig. 4(b) was approximately 0.055/ksi. Since the data points in Fig. 4(a) were spread more evenly over the whole stress range than those in Fig. 4(b), which were concentrated over the 3.5 to 5 ksi range, the slope determined from Fig. 4(a) should be more accurate. (This is reflected by the "coefficient of determination," R^2 , value for the least-squares fit [6]. $R^2 = 0.85$ and 0.37 for the data in Figs. 4(a) and 4(b), respectively. Note that greater values of R^2 indicate a better fit, with $R^2 = 1$ being a perfect fit.) Therefore, 0.065/ksi can be taken as the representative value for the stress sensitivity of the NLH method. The scatter in the NLH anisotropy measurements was approximately 0.06, as determined by the "standard deviation of y estimate" (66% of the data would fall within ± 0.06 of the least-squares fitted line). This corresponds to approximately ± 0.92 ksi accuracy in stress measurements.

For a given stress value, the NLH anisotropy obtained from location No. 1 [Fig. 4(b)] was approximately 0.07 larger than that obtained from location No. 5 [Fig. 4(a)]. This difference may be due to (1) difference in residual stresses induced during rail fabrication or straightening operations and/or (2) difference in the actual longitudinal forces. To verify the causes, de-stressing of the rails at the two testing locations would be required.

In addition, the observed stress sensitivity, 0.065/ksi, compared fairly well with 0.08/ksi obtained from a 3-foot long sample of 119 lbs/yard weight rail in the limited laboratory investigation mentioned above [5]. This may suggest that the NLH is not highly sensitive to differences in rail material.

CONCLUSIONS

Based on the results of the field testing, the following conclusions can be made:

- (1) The NLH method can measure longitudinal stress in rail under field conditions.
- (2) The observed stress sensitivity of the NLH anisotropy was approximately 0.065/ksi (1 ksi = 1000 psi).
- (3) The accuracy of stress measurements was approximately ± 0.92 ksi.

In order to develop a field NLH instrument for rapid survey of stress states in rails, further research and developmental efforts are needed, including:

- (1) Investigation of stress dependence of NLH in various types of rail.
- (2) Investigation of effects of residual stress produced during fabrication or straightening operations.
- (3) Investigation of effects of scanning speed.
- (4) Optimization of sensing probe and data acquisition.
- (5) Development of test procedures and mechanical devices to accommodate field survey.

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