FINITE ELEMENT MODELING OF THE BULK MAGNITIZATION OF RAILROAD WHEELS TO IMPROVE TEST CONDITIONS FOR MAGNETOACOUSTIC RESIDUAL STRESS MEASUREMENTS

J. P. Fulton and B. Wincheski
Analytical Services and Materials, Inc.
107 Research Drive
Hampton, VA 23666

M. Namkung
NASA, Langley Research Center
Hampton, VA 23681

D. Utrata
Association of American Railroads
3140 S. Federal Street
Chicago, IL 60616

INTRODUCTION

The magnetoacoustic measurement technique has been used successfully for residual stress measurements in laboratory samples[1-4]. However, when used to field test samples with complex geometries, such as railroad wheels, the sensitivity of the method declines dramatically[5,6]. It has been suggested that the decrease in performance may be due, in part, to an insufficient or nonuniform magnetic induction in the test sample[6]. The purpose of this paper is to optimize the test conditions by using finite element modeling to predict the distribution of the induced bulk magnetization of railroad wheels. The results suggest that it is possible to obtain a sufficiently large and uniform bulk magnetization by altering the shape of the electromagnet used in the tests. Consequently, problems associated with bulk magnetization can be overcome, and should not prohibit the magnetoacoustic technique from being used to make residual stress measurements in railroad wheels.

We begin by giving a brief overview of the magnetoacoustic technique as it applies to residual stress measurements of railroad wheels. We then define the finite element model used to predict the behavior of the current test configuration along with the nonlinear constitutive relations which we obtained experimentally through measurements on materials typically used to construct both railroad wheels and electromagnets. Finally, we show that by modifying the pole of the electromagnet it is possible to obtain a significantly more uniform bulk magnetization in the region of interest.

THE MAGNETOACOUSTIC TECHNIQUE

The technical basis for the magnetoacoustic technique comes from the observation that the velocity of an ultrasonic wave in a ferrous material is affected by its magnetic domain structure. Furthermore, the magnetic domain structure is sensitive to states of stress and externally applied magnetic fields. Thus, if the velocity of an ultrasonic wave in a stressed and magnetized ferromagnetic material is monitored as the magnetizing field is changed, a change in the velocity unique to the materials state of stress is observed. Optimum results seem to occur when the magnitude and orientation of both the stress and magnetizing field are uniform and perpendicular to the direction of propagation of the ultrasonic wave[6].

The magnetoacoustic technique has been applied to railroad wheels which are particularly susceptible to residual stress along their circumference[5,6]. The tests were designed to induce a uniform magnetic flux, of sufficient intensity, in the region where an ultrasonic wave propagates perpendicular to the magnetizing field. For bulk residual stress measurements of the wheel the transducer is located on the front of the rim and sends a shear wave through the wheel's cross-section as shown in Fig.1. The flux is induced by an electromagnet whose poles are placed on the surface of the wheel rim several centimeters on either side of the transducer.

Utrata[6] suggests that for optimal test conditions to exist, both the stress and induction in the region where the ultrasonic wave propagates should be uniform. Since it is not possible to control the state of stress of the wheel we can only hope to a achieve a uniform inductance in this region. The complex geometry of the wheel, however, makes the rims magnetization difficult. To account for the wheel's complex geometry, the electromagnet's poles were designed and positioned in a way that was thought would best induce the desired magnetizing field. The results of tests on actual wheels, however, proved inconclusive. Consequently, a quantitative assessment of the magnetic field distribution in the wheel was performed to study the effects further[6]. A finite element analysis of the test revealed that the induced field was not uniform across the rim which could have a detrimental effect on the test results. In this paper we verify the finite element analysis reported on in [6], and then show where modifications to the electromagnet can be made which significantly reduce the effects of this potential problem.

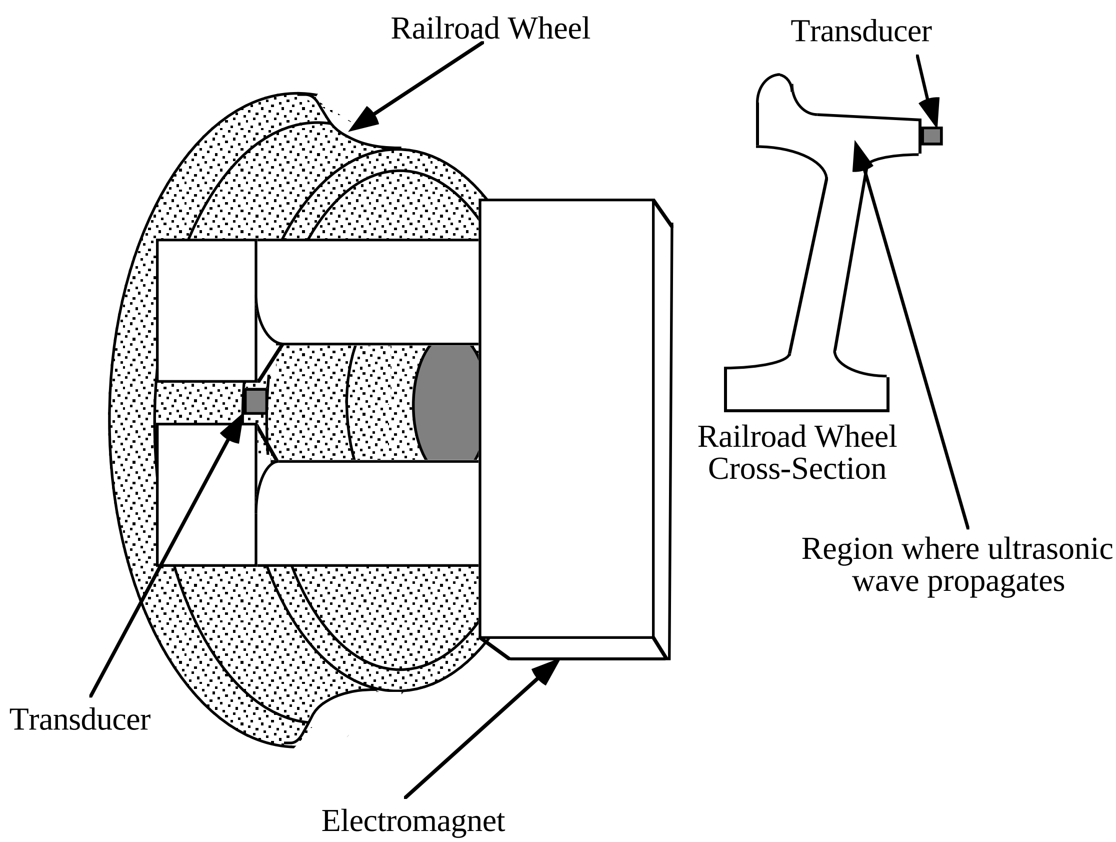

Fig. 1. Schematic of the current test set-up along with a wheel cross-section.

FINITE ELEMENT ANALYSIS

A finite element model of the set-up in Fig.1 was constructed using COSMOS/M[1] a finite element package developed by Structural Research and Analysis Corporation. The analysis is based on dividing the total magnetic field intensity $\vec{H}$ into two parts

$$\vec{H} = \vec{H}_s + \vec{H}_m \tag{1}$$

where $\vec{H}_m$ is the induced magnetization field and $\vec{H}_s$ is the current source field in free space and is calculated from the Biot-Savart equation

$$\vec{H}_s(r) = \frac{1}{4\pi}\int_{V_s} \frac{\vec{J}_s x (\vec{r} - \vec{r}_s)}{|\vec{r} - \vec{r}_s|^3} dV_s \tag{2}$$

$\vec{H}_m$ can be expressed as a function of a scalar potential ψ such that

$$\vec{H}_m = -\nabla \psi \tag{3}$$

Using the above relations with Maxwell's equations the following expression is obtained

$$\nabla \bullet \mu \nabla \psi - \nabla \bullet \vec{H}_s = 0 \tag{4}$$

where $\mu(B)$ is the magnetic permeability.

The finite element method used in COSMOS is based on the stationarity of a suitable energy functional for (4). For nonlinear problems, Newton's method is used which can be expressed in the following matrix form:

$$([K]_L + [K]_{NL})\Delta\psi^i = [R] - [K]_L \psi^{i-1} \tag{5}$$

where

$[K]_L$	= Linear stiffness matrix
$[K]_{NL}$	= Nonlinear stiffness matrix
$[R]$	= Loading vector
$\Delta\psi^i$	= magnetic potential increment vector at iteration (i)
ψ^{i-1}	= magnetic potential vector at iteration (i-1)

FINITE ELEMENT MODEL AND RESULTS

Geometry and Finite Element Mesh

Measurements of the geometry of the wheel and electromagnet were taken from actual components used in the testing. The problems symmetry allowed us to model only half of the electromagnet. Ordinarily, half of the wheel would also be modeled, however, due to the localized nature of the magnetic field and computer memory constraints only a 60° section of the wheel was modeled. This can cause a slight increase in the inductance of the wheel and its effect would increase with the electromagnets' current, however, the effect on the inductance in the region of interest should be minimal.

In regions where either the concentration of the magnetic field is low, or information on field quantities was not needed, a coarse mesh was used. A finer mesh is used for the region between the two pole pieces where detailed information and accuracy are required. Fig. 2 shows the meshed wheel along with the electromagnet. A cylindrical coil is actually surrounding the core of the electromagnet, but is not shown in the figure. The wheel was

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1. COSMOS/M is a registered trademark of Structural Dynamics and Research Corporation, 1661 Lincoln Blvd., Suite 200, Santa Monica, CA 90404

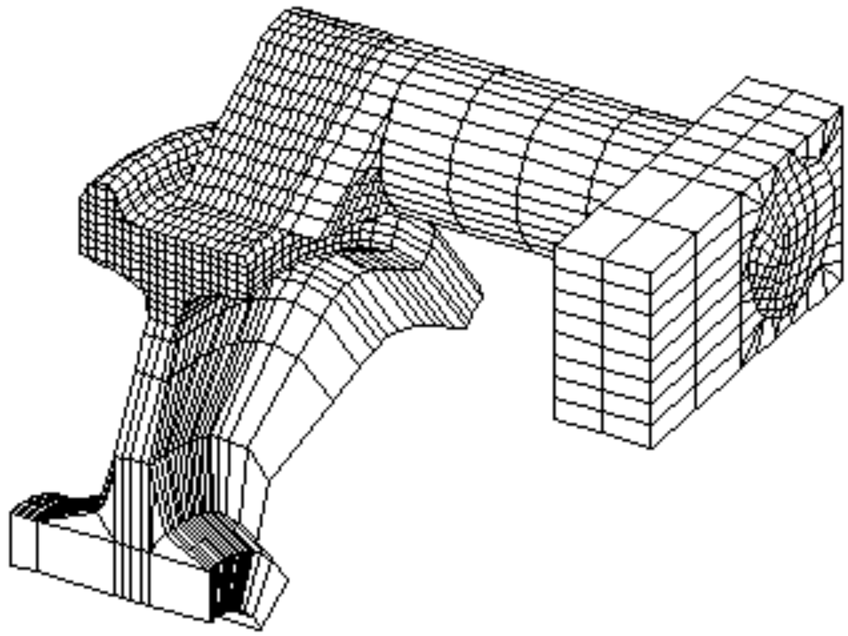

Fig. 2. Finite element model of the current test configuration.

meshed with 3162 8-node brick elements and an additional 2090 brick elements were used in the electromagnet. The wires encircling the cylindrical core are modeled using a 3-d cylindrical current source that surrounds the core.

Constitutive Relations

The nonlinear constitutive properties of the wheel and electromagnet are incorporated into the model by using experimentally determined B-H curves for each of the materials. For the railroad wheel a 0.68% carbon steel was used while a 0.1-0.15% carbon steel was used for the electromagnet. The results were obtained by using a calibrated coil encircling the test sample to determine the B field as a function of the induced voltage and a magnetic potentiometer (Chattock coil) on the surface of the sample to determine the H field as a function of the induced voltage (see Fig.3). Then having both B and H as a function of the voltage V, we simply eliminated V to obtain the B-H curves shown in Fig. 4. A more complete description of the theory behind the technique can be found in Cullity [7].

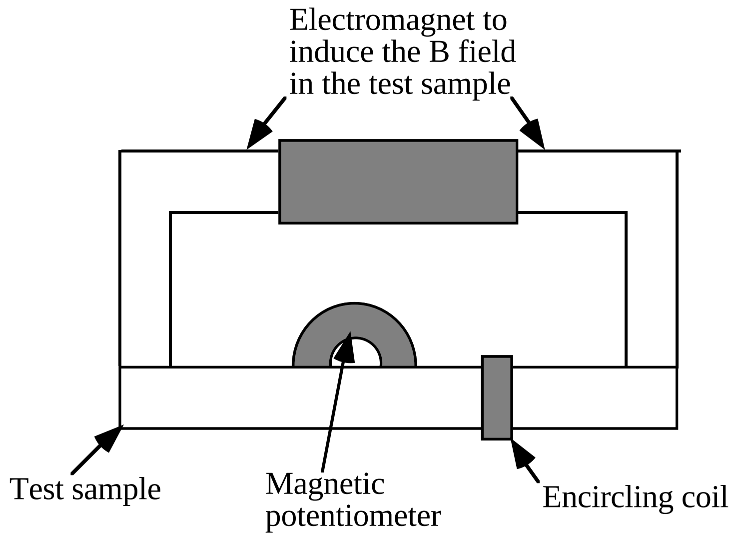

Fig. 3. Experimental set-up for B-H curve determination.

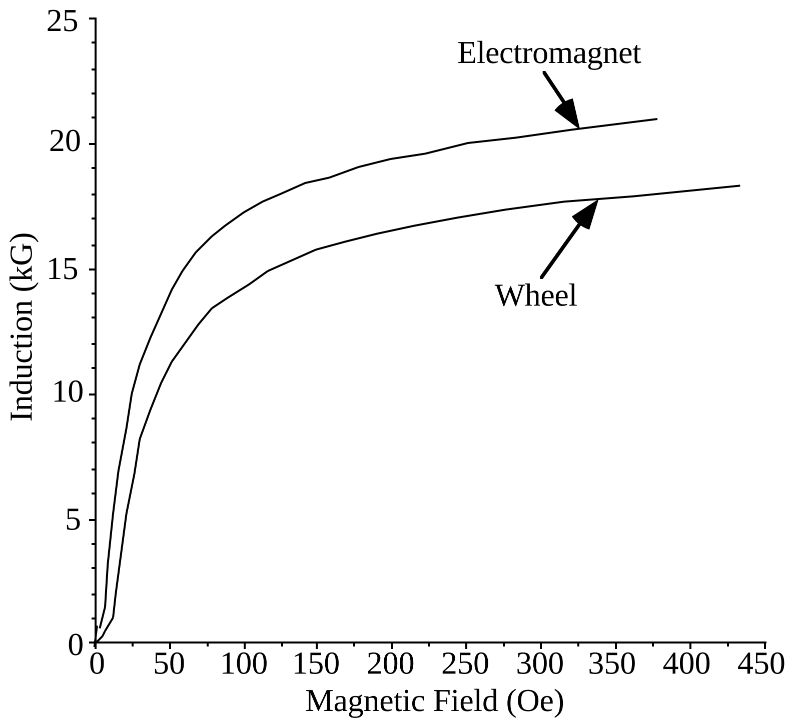

Fig. 4. B-H curves for wheel and electromagnet.

<u>Typical Inductance Profiles and Comparison of Results</u>

The model was run using an applied current of 1, 2, 4, 6 and 8 Amps. A typical flux profile for an applied current of 2 Amps is shown in Fig.5. The resultant flux field ranges from about 13 G to 19 kG, with the larger inductance concentrated in the electromagnet core. The zoomed-in portion of the figure is the region in which the ultrasonic wave propagates. This region was displayed using a different flux scale and shows a variation of about 9.9-11.2 kG. It also illustrates the rather large flux gradient as you move from the front (right) to the back (left) of the wheel's rim.

We also noticed a distinct difference between our results and those reported previously by Utrata[6]. With a current of 2 Amps the induction at a cross-section of the rim where the ultrasonic wave propagates was previously computed to range from about 12.2-13.3kG. However, our results showed a much lower range of 9.9-11.2kG. On the other hand, when the current is increased to 6 Amps our results ranged from 13.5-14.9 kG (very close to saturation, see Fig.4) while the previous results were 12.9-13.7 kG. Although a slight variation at the higher current level could arise due to our modeling a smaller portion of the wheel, there should not be such a distinct difference at 2 Amps. It is quite possible that the differences are due to different constitutive laws employed in the models, however, this should be investigated further. A more complete comparison of the results is given in Fig. 6.

MODIFIED ELECTROMAGNET AND RESULTS

The analysis revealed that the field along the back side of the wheel was consistently smaller than on the front portion of the wheel. Thus, to produce a larger field at the rear of the wheel and at the same time obtain a more uniform field across the cross-section, we extended the pole of the electromagnet over the rear portion of the wheel. This required an additional 1199 8-node brick elements which followed the contour of the wheel (see Fig.7).

The modified model was then run with an applied current ranging from 1 to 8 Amps. A comparison of the bulk magnetization across a wheel rim cross-section for the two different pole geometries is shown in Fig. 8. The results show that the modified pole piece induces a significantly more uniform flux field across the wheel rim cross-section then the original electromagnet. The improvement is most evident at the lower range of current values (1-4 Amps). There is also an increase in the magnitude of the inductance for higher

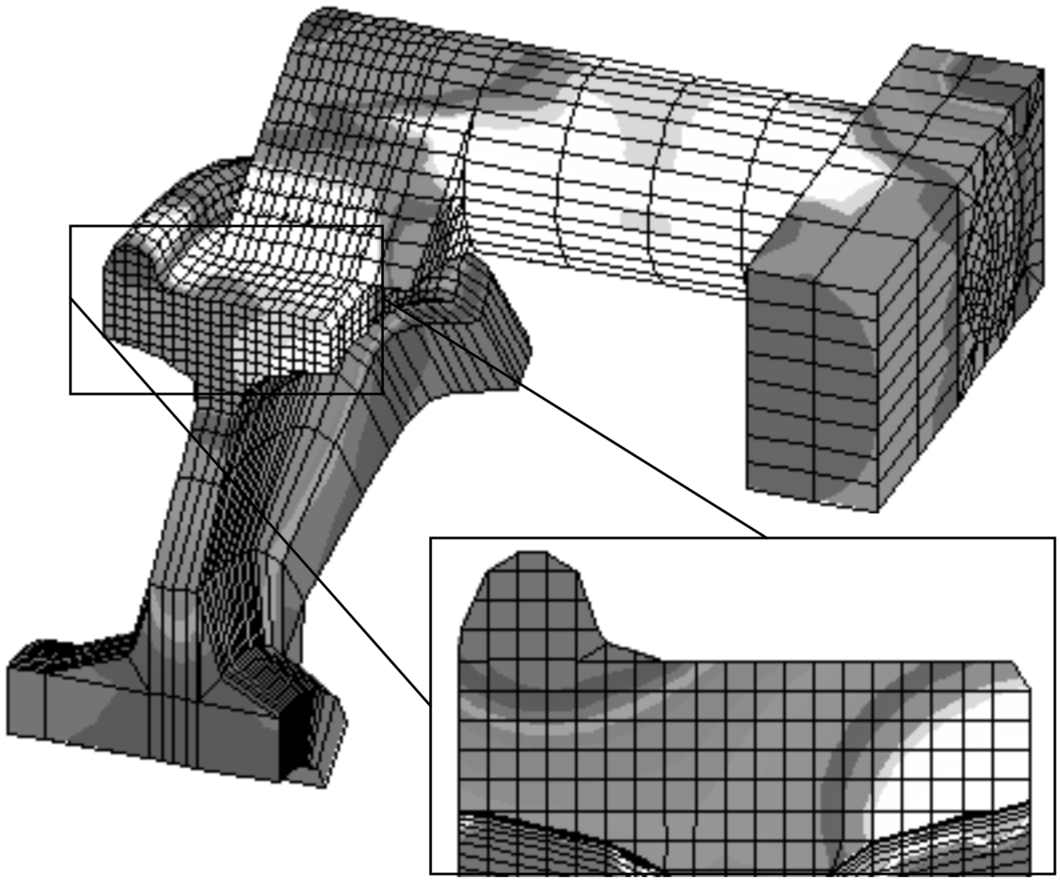

Fig. 5. Magnetic flux profile in wheel and electromagnet with 2 Amps of applied current.

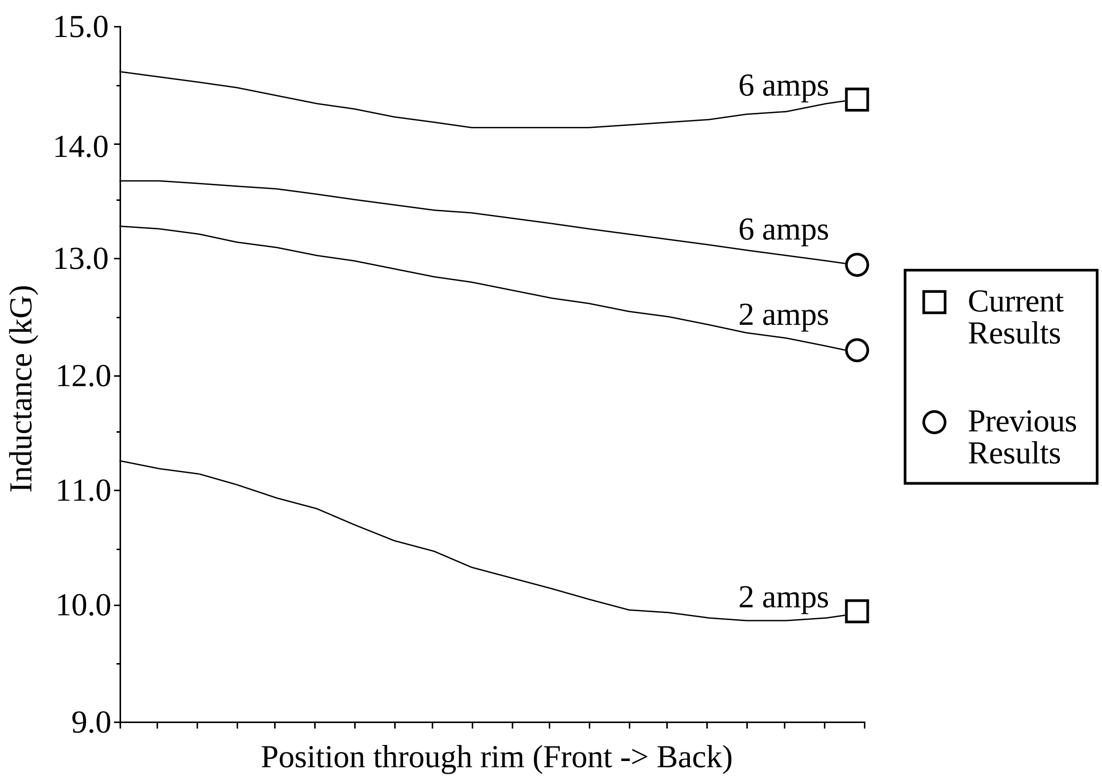

Fig. 6. Comparison of new flux field results with those reported on in [6] along a cross-section of the railroad wheel

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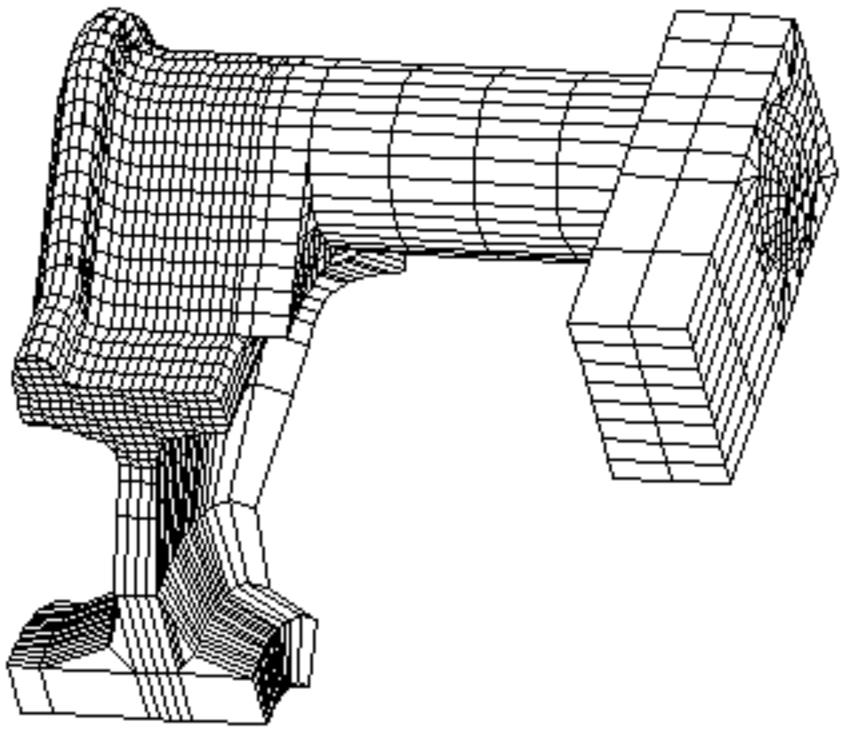

Fig. 7. Finite element model of the wheel and modified electromagnet.

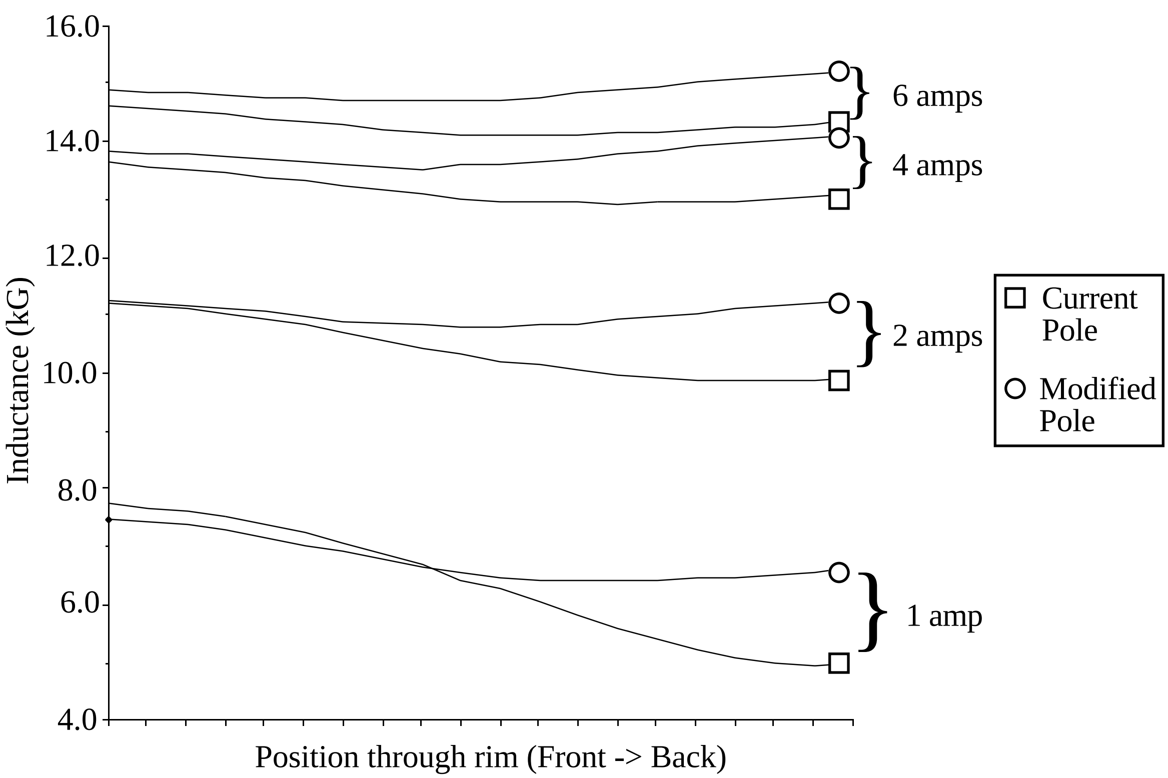

Fig. 8. Comparison of magnetic induction across a wheel rim cross-section.

current values, which is more pronounced along the back portion of the rim.

SUMMARY

The results of our analysis clearly indicates that making slight modifications to the shape of the electromagnet can have a significant impact on the bulk magnetization of railroad wheels. We have demonstrated that by changing the geometry of the electromagnet's poles it is possible to obtain a fairly large and uniform inductance in the rims of railroad wheels. These changes should increase the effectiveness of the magnetoacoustic technique for measuring the residual stress in the rims of railroad wheels.

Further experimental tests should be performed to study how a magnetic flux gradient within the test sample effects the sensitivity of the magnetoacoustic technique. If necessary, further modifications to the electromagnet's poles could be made to obtain a more suitable flux distribution. The results of the finite element analysis along with the experimental results would be useful in constructing a more complete model to refine our understanding of how the magnetoacoustic technique works. This would enable us to make improvements to the technique and, as a result, improve on its sensitivity.

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