Nonlinear Eddy Current Technique for Characterizing Case Hardening Profiles

Shiu Chuen Chan[1], Raimond Grimberg[3], Jose A. Hejase[1], Zhiwei Zeng[2], Peter Lekeakatakunju[1], Lalita Udpa[1], *Fellow, IEEE*, and Satish S. Udpa[1], *Fellow, IEEE*

[1]Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824 USA
[3]National Institute of R&D for Technical Physics, Iasi, Romania
[2]Department of Aeronautics, Xiamen University, Fujian, 361005 China

Industrial components are often case hardened to improve their strength and wear characteristics. Traditionally, component samples are collected from the production line at specific intervals and destructively tested for case depth profile assessment. This process is time-consuming, laborious, and can potentially allow an improperly treated component to escape detection. This paper presents a novel nonlinear eddy current technique for assessing the case hardening profile based on the premise that the magnetic characteristic of the case hardened region is different from that of the host material. A custom electromagnetic excitation-sensor array is used to both apply sinusoidal excitations to the component and measure the nonlinear response at multiple excitation frequencies and spatial locations, taking advantage of the different penetration regions due to the skin depth phenomenon. Each response signal obtained from the component under test is compared with that from a reference component subjected to the same excitation. Two pattern recognition algorithms (an artificial neural network and the Iterative Dichotomiser 3 (ID3) algorithm) are then used to process selected characteristics of the difference signal to determine the case depth profile of the component. The nonlinear eddy current technique has been applied to evaluate the case hardening profile of automotive bearing assemblies. This problem is challenging due to the variations in geometry across assemblies as well as the limited accessibility to the case hardened surface. In the neural network test, the system achieved a 95.77% accuracy. For the ID3 algorithm, the system achieved a 95.65% accuracy. These results demonstrate that the nonlinear eddy current inspection technique is highly promising in characterizing the case profile of induction hardened parts.

Index Terms—**Automotive bearing assembly, case hardening profile evaluation, Iterative Dichotomiser 3 (ID3) algorithm, neural network, nondestructive testing, nonlinear eddy current.**

I. Introduction

INDUSTRIAL components are often case hardened to improve their strength and wear characteristics. An industrial component whose case hardening profile is of great importance is the automotive wheel bearing assembly shown in Fig. 1. The bearing assembly is made from 1050 steel and consists of a forged core (Fig. 2) surrounded by ball bearings that are held in place by an inner and outer retaining ring. The exterior surface of the core is case hardened to reduce mechanical wear due to contact with the ball bearings. The case depth, in this case, is critical: a case profile that is too shallow provides inadequate protection against wear, which may in turn lead to bearing failure and wheel lock-up. An over-penetrated case profile (i.e., too deep) may render the core brittle and prone to fracture when in use. Both of these scenarios lead to important safety concerns. As a result, there is a significant interest in characterizing the case hardened profile and evaluating the case depth of the wheel bearing assembly nondestructively.

The bearing assembly poses significant challenges for classical nondestructively evaluation approaches (e.g., the magneto-acoustic [1], [2], photothermal [3], or ultrasound [4], [8] methods) for determining either the surface hardness or case profile as these approaches are better-suited for applications where the hardened surface is readily accessible. Unfortunately, this is not the case with the wheel bearing assembly. In practice, any nondestructive case depth evaluation on the assembly must be carried out through the recessed opening of the inboard stem-end at the top of the core as shown in Fig. 1. To further complicate matters, the geometry of the recessed opening varies from one assembly to another as this area is considered non-functional and its dimensions are, therefore, not fully specified by the manufacturer. The proposed inspection system has been designed to address this challenging problem. The principle of the nonlinear eddy current inspection system [4], [8] is suitable for other case profile characterization applications as well.

Fig. 1. Automotive wheel bearing assembly consisting of a core piece surrounded by ball bearings held in place by an inner and outer retaining ring.

Fig. 3 shows the cross-sectional profile of the wheel bearing core. The lateral exterior surface of the core is case hardened and the resulting hardening profile appears as darkened regions in the figure. The dimensions "L" and "D" in Fig. 3 represent the effective extent and maximum case depth, respectively, of

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Fig. 2. Wheel bearing assembly core. The inner bearing retaining ring is shown underneath the top flange, covering the case hardened region of interest.

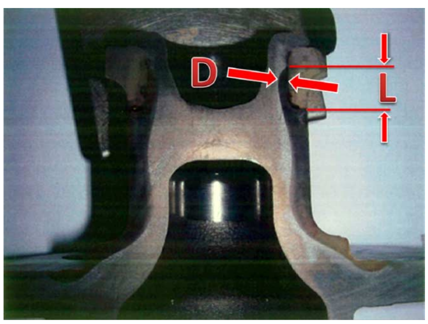

Fig. 3. Cross-sectional profile of the bearing assembly core. The maximum case depth, D, and the effective extend, L, of the profile are used for case profile assessment.

the region and are used for case profile assessment. For the wheel bearing assembly, an acceptable case profile consists of an L-dimension between 9–13 mm and a core depth "D" between 3.75–5 mm.

II. Nonlinear Eddy Current Inspection System

A. Nonlinear Magnetic Effects

The proposed inspection system applies a sinusoidal magnetic field (Fig. 4(a)) to excite the bearing core. The strong excitation field causes the material to operate in the nonlinear region of the magnetization characteristic during a portion of the excitation cycle. This is evident both from the response shown in Fig. 4(b) to a sinusoidal excitation signal as well as the Lissajous pattern shown in Fig. 5. The inspection technique exploits the differences in magnetization characteristics between the untreated and case hardened steel. The custom inspection probe shown in Fig. 6 employs an array of detection coils to determine the magnetization at different locations. This information is then used to estimate the deviation of the case hardening profile of the test specimen from that of a reference specimen.

B. Inspection Approach

The inspection approach compares the nonlinear responses between a reference and test bearing assembly. Fig. 7 shows the schematic diagram of the inspection system. A sinusoidal excitation signal is applied to the series-connected excitation coils

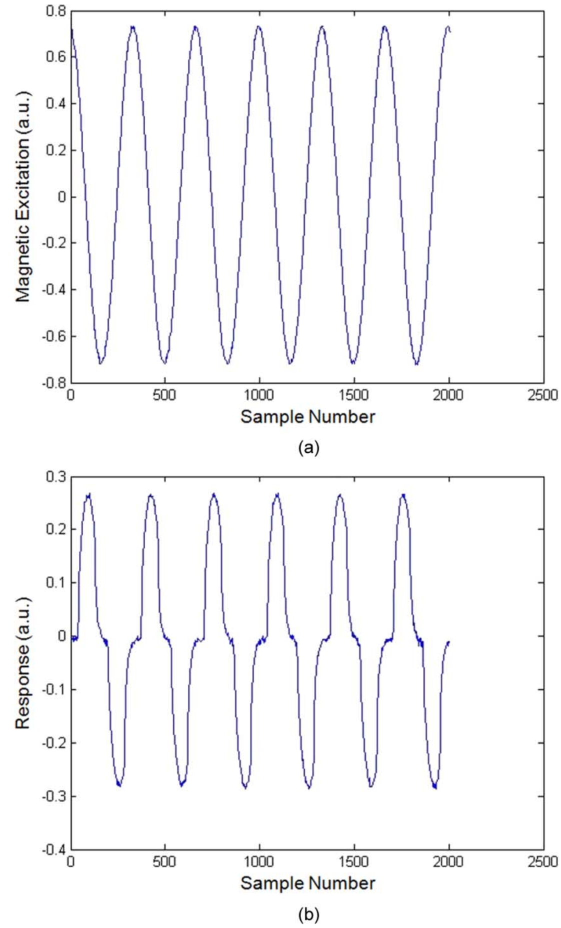

Fig. 4. Sinusoidal magnetic excitation (a) and the resulting nonlinear response of the core. (The unit for the y axis is arbitrary.)

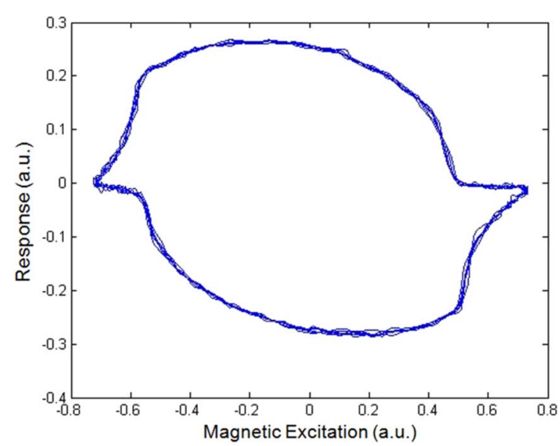

Fig. 5. Lissajous pattern formed from the nonlinear response of the core and the strong sinusoidal magnetic excitation.

to subject both the reference and test parts to the same magnetic field. Each sensor assembly in Fig. 7 consists of 5 sensor coils (as shown in Fig. 6). The corresponding sensor coils from the two assemblies are differentially connected such that the output represents the difference signal between the two coils. If the case profile of the test sample is similar to that of the reference sample, the amplitude of the output signals generated by the five coil pairs would be approximately zero. Otherwise, one or more

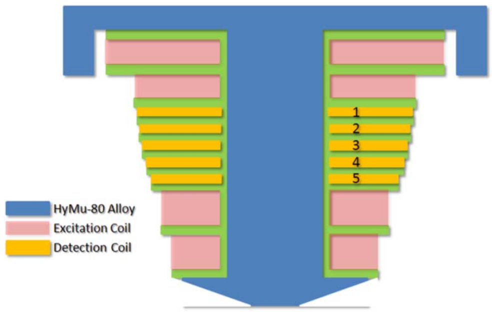

Fig. 6. Schematic diagram of the electromagnetic sensor assembly showing arrays of excitation and detection coils with a high permeability alloy core.

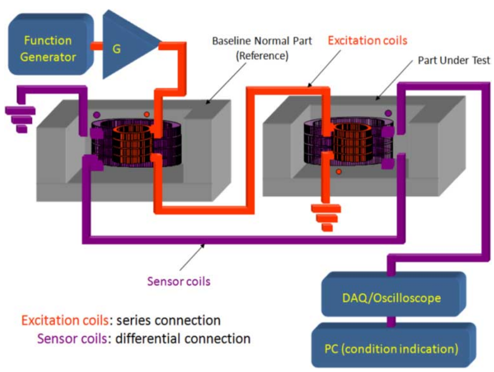

Fig. 7. Schematic diagram of the nonlinear eddy current inspection approach.

of the outputs will be non-zero. The output signals are then processed and examined to determine the characteristics (L-dimension and core depth) of the case hardening profile.

C. Electromagnetic Sensor Assembly

The electromagnetic sensor assembly consists of 4 excitation and 5 detection coils. It employs a ferromagnetic core made from HyMu "80" alloy (Scientific Alloys, Inc., Westerly, RI) to reduce magnetic flux leakage and ensure penetration of the applied magnetic field into the case hardened region of the bearing assembly. Two sensor assemblies—one for the reference and the other for the component under test—are connected in series in the inspection system. As the excitation coils have negligible capacitances, the series connected coils produce a strong ($\sim$1.3 T) magnetic field at a frequency between 5–300 Hz to excite each component. The detection coils, meanwhile, form an array that is sensitive to spatial variations in the response field.

D. Processing Scheme and System Parameters

Fig. 8 shows the processing scheme for the nonlinear eddy current inspection system. In this system, the difference signals from the five corresponding detection coil pairs are sampled by a multi-channel data acquisition system. The frequency spectrum of each difference signal is then obtained and selected characteristics of the spectrum are extracted to form a feature vector representing the signal. Signal classification algorithms are then applied to the feature vector and the results are analyzed to determine the geometric characteristic of the case hardening profile.

The inspection system applies excitation signals at 5, 100, and 300 Hz to investigate the nonlinear responses due to flux penetration at different depths. To reduce the complexity of the classification algorithms, only outputs from sensor coils 1, 2, 3, and 5 are used to generate the feature vector for the part under test.

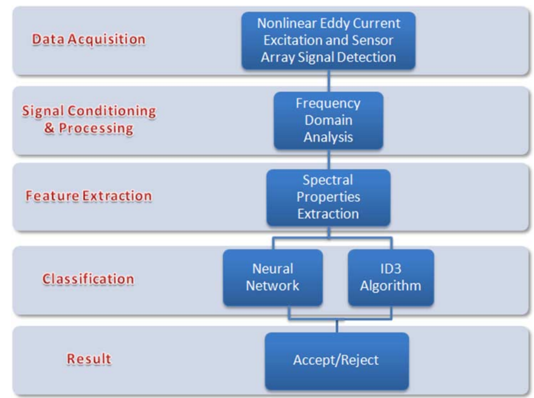

Fig. 8. Processing scheme for the nonlinear eddy current inspection system.

E. Feature Vector Formation

From the frequency spectrum of each difference signal, the ratio between the third and first harmonics, and as well as that between the fifth and first harmonics, are obtained. Thus, for four difference signals collected at each excitation frequency, 8 ratios are generated. For the three excitation frequencies used in the inspection system, a total of 24 ratios are calculated. These 24 harmonic ratios form the feature vector for the bearing assembly part under test. Signal classification algorithms are then applied to the feature vector to characterize the underlying case profile.

F. Signal Classification Algorithms

Two signal classification algorithms are used in the nonlinear eddy current inspection system: an artificial neural network [5] and the Iterative Dichotomiser 3 (ID3) algorithm [6], [7]. The neural network implements a multilayer perceptron model with a backpropagation training algorithm. The network consists of one input, two hidden, and one output layer with a 24-8-4-1 topology. At the hidden and output nodes, the log-sigmoid transfer function $a = 1/(1 + e^{-n})$ that relates the input n to output a is used. The output of the neural network presents one of the two states: accept or reject (for the bearing assembly under test). The criteria for acceptance and rejection are given in Section III.

The Iterative Dichotomiser 3, or ID3, is a mathematical algorithm by Ross Quinlan [6] for constructing decision tree classification models. The ID3 algorithm has been implemented in the See5 data mining software by RuleQuest Research Pty. Ltd. of New South Wales, Australia. This software supports an enhancement feature called boosting. The idea of boosting is to utilize more than one classifier in each application. For instance, when a new input vector is to be classified, each member of a group of classifiers will indicate an output class and the indications from of all the classifiers are tallied to determine the final class (by majority).

Release 1.20a of See5 has been used to generate the decision tree for classifying the case profile conditions of the automotive bearing assemblies. The software is used with 14 boosting trials. The input file to the software consists of both training and test data. From the training data the ID3 algorithm selects the best

TABLE I
BEARING ASSEMBLIES MASTER LOTS SPECIFICATIONS

Lot	L-Dimension (mm)	Core Depth (mm)	Condition
1	10.6	5	Accept
2	11.7-11.82	4	Baseline Accept
3	12.75	3.5	Baseline Reject
4	13.9-14	2.8	Reject

TABLE II
NEURAL NETWORK CLASSIFICATION RESULTS

Sample Group	No. of Parts Tested	No. of Parts Correctly Classified	Accuracy
Accept	13	13	100%
Baseline Accept	20	20	100%
Baseline Reject	21	18	85.71%
Reject	17	17	100%

attributes to form the nodes of a decision tree. From the generated tree, a set of IF-THEN-ELSE rules is deduced which is then used to classify the test cases.

III. RESULTS

Master lots of bearing assemblies with various known L-dimensions and associated core depths have been custom manufactured for evaluating the inspection system. The master lots belong to four classes based on the manufacturer's specifications: Accept, Baseline Accept, Baseline Reject, and Reject. The specifications for these master lots are given in Table I. Note that the Baseline Accept and Baseline Reject lots border the acceptance threshold (a core depth of 3.75 mm or more) for the part.

The inspection system was tested with these master lots using both the neural network and ID3 algorithms. In the neural network test, the Baseline Accept lot was combined with the Accept lot, while the Baseline Reject lot was combined with the Reject lot, to form two training lots. From these two lots, 46 Accept and 52 Reject samples were used for training. The classification results of 33 Accept and 38 Reject previously untrained samples are shown in Table II. The system presented a 14.29% error in classifying the Baseline Reject parts and achieved a 100% accuracy in identifying the remaining parts. Based on the choice of training data used, the neural network classifier may be over-trained on 3 classes and under trained on the 4th class resulting in the larger error in the Baseline Reject parts. In typical industrial practice, the Baseline Reject and Reject parts are both rejected by the quality control process. With this consideration, the inspection system presented a 7.9% error in classifying the rejectable parts, yielding an overall accuracy of 95.77% with the neural network classifier.

For the ID3 algorithm, 100 samples were used for training and 69 samples for testing. The composition of the training and testing sample groups, as well as the classification results, are listed in Table III. The system correctly classified the Accept parts, and presented a 5%, 4.77% and 6.25% error for the Baseline Accept, Baseline Reject and Reject parts, respectively. With

TABLE III
ID3 ALGORITHM CLASSIFICATION RESULTS

Sample Group	No. of Training Parts	No. of Test Parts	No. of Parts Correctly Classified	Accuracy
Accept	17	12	12	100%
B. Accept	30	20	19	95%
B. Reject	30	21	20	95.23%
Reject	23	16	15	93.75%

the ID3 classifier, the decision boundary is derived by minimizing the average error which is distributed somewhat equally among the 3 classes as shown in Table III. In the context of industrial practice, the system achieved a 96.8% accuracy in indentifying the acceptable parts and 94.6% for the rejectable parts, demonstrating an overall accuracy of 95.65% with the ID3 algorithm.

IV. CONCLUSION

A novel nonlinear eddy current inspection technique has been developed for characterizing the case depth profile of a component. The technique is suitable for both general applications as well as in situations where the case hardened region of the component is not readily accessible. Application of the technique to characterize automotive bearing assemblies with challenging geometries has shown an approximately 95.7% accuracy in identifying the acceptable assemblies. The technique is highly promising in characterizing the case profile of induction hardened parts.

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