Eddy Current Examination of Gear Systems

This nondestructive testing method can save time and labor.

Christopher E. Collins

Nondestructive examination (NDE) of ferrous and nonferrous materials has long proved an effective maintenance and anomaly characterization tool for many industries. Recent research has expanded its applicability to include the inspection of large, open gear drives. Difficulties inherent in other NDE methods make them time-consuming and labor-intensive. They also present the user with the environmental problem of the disposal of used oil. The eddy current method addresses these problems.

Nondestructive examination is the inspection of an object or material in a manner that does not impair its future usefulness. The form, fit and function of the test piece or material are not damaged by the examination. Standard NDE techniques currently available for detection of surface flaws in gear systems include dye penetrants, magnetic particle examination and specialized ultrasonic procedures. A list of the five major NDE field techniques and a brief description of each method is found in Table 1.

The magnetic particle examination method is commonly used to detect surface flaws in the tooth roots in gear systems. This technique, while simple to perform, is very complex because of the number of variables that must be considered. Does the inspector use wet or dry media? Visible or fluorescent magnetic particles? Is proper lighting available for the technique being used? Is the test material completely clean (lubricant free)—an absolute necessity in the magnetic particle and dye penetrant methods?

Eddy Current Testing Principles

Eddy current examination is based on the process of electromagnetic induction. Alternating current flowing through a coil produces a magnetic field (primary magnetic field). If a conductive test piece is placed in close proximity to the coil, the changing magnetic field induces a current in the test piece. The induced electromagnetic field provides for eddy current flow.

The flow of eddy currents depends on numerous variables related to test piece properties and the electronic characteristics of the test equipment. As eddy currents flow, they generate their own magnetic field (secondary

Table 1 — The Five Major Nondestructive Examination Techniques

Ultrasonic Examination. Most ultrasonic testing concentrates on the interior of the component. The most common method is to use a transducer to send ultrasonic vibrations through the test object. The transducer converts electrical signals, sent from an oscilloscope, into ultrasonic vibrations. Interior defects show up in the sound waves reflected back to the transducer. The transducer converts the sound energy back to an electrical signal for display on the oscilloscope. Examining a weld or component can be quick and economical, but the skill of the inspector, coupled with the expense of his training and equipment, is a limiting factor.

Eddy Current Examination. Eddy current testing uses an alternating magnetic field to induce small electric currents in the component being examined. These currents are affected by surface or slightly sub-surface abnormalities in the components. Defect indications appear on the instrument CRT. Eddy current testing is limited to conductive materials. Care must be taken to avoid false indications due to part geometry or permeability variations (ferromagnetic materials).

Magnetic Particle Examination. The magnetic particle examination technique detects surface and slightly sub-surface indications. While providing a magnetizing force over a test area of the component, the inspector sprays a suspension of colorized iron filings (either dry or wet fluorescent) within the magnetized area. The iron filings align themselves along the artificial magnetic field created by any defects. The process is simple to use and some methods do not require extensive training. The test surface should be completely cleaned before applying the magnetic particles. Many components require demagnification after testing.

Liquid Penetrant Examination. Penetrants detect surface flaws by permeating cracks or pores. A small amount of penetrant is applied to a test area. After a specified "dwell time" has elapsed, the penetrant is removed from the surface. A blotter-like developer is applied over the test surface. The developer draws excess penetrant from the defects. The penetrant is either a color that contrasts strongly against the component background, or it is fluorescent. Although simple to use, penetrants can miss defects if the surface is not adequately cleaned or the flaw is obstructed with smeared metal.

Radiographic Examination. Radiography employs X-rays or gamma rays to penetrate the test object. It displays a permanent picture of the test object's interior on radiographic film. Radiographic limitations include the need for adequate component geometry, strict security of the test area and time to develop and interpret the test film. Radiographic examiners require extensive training.

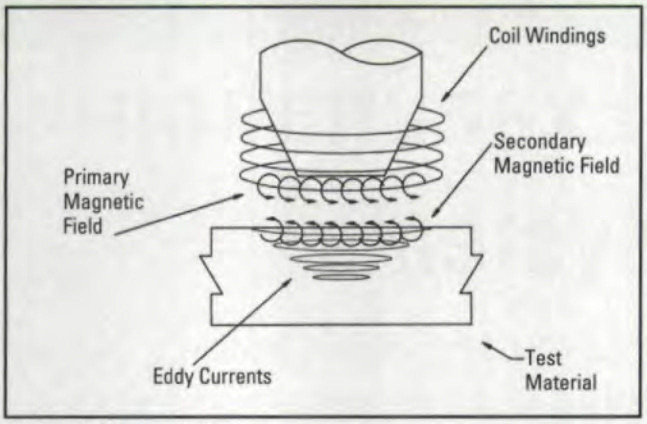


Fig. 1 — Eddy current flow.

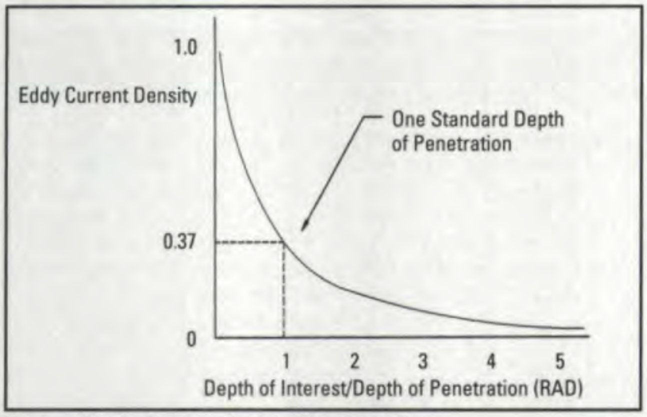


Fig. 2 — Depth of penetration of eddy current flow.

Table 2 — Eddy Current Examination Formulas

One standard depth of penetration in inches: $\delta = 1.98 \sqrt{[\rho/(f^*\mu_r)]}$

where: ρ = resistivity in micro-ohm-centimenters ($\mu\Omega$cm)
f = test frequency in Hertz (Hz)
μ_r = magnetic permeability relative to air (dimensionless)

For non-ferromagnetic materials, magnetic permeability is constant ($\mu_r = 1$),

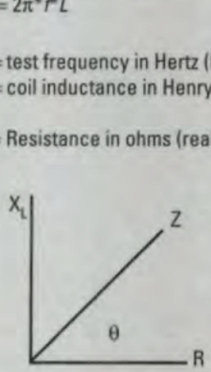
therefore: $\delta = 1.98 \sqrt{(\rho/f)}$

Phase Diagram Construction:

Inductive reactance (Imaginary component) in ohms:
$X_L = 2\pi^* f^* L$

where: f = test frequency in Hertz (Hz)
L = coil inductance in Henrys (H)

R = Resistance in ohms (real component)



Initial coil impedance: $Z = \sqrt{(X_L)^2 + (R)^2}$

Phase lag: $\theta = \arctan(X_L/R)$

magnetic field), which opposes the primary magnetic field (See Fig. 1).

Distortions in the secondary magnetic field created by surface or sub-surface flaws change the impedance of the coil. The eddy current test equipment senses these differences and displays the changes on an oscilloscope CRT, strip chart or other display recording device. Electrical conductivity differences between flaws (cracks) and the homogeneous area of the test piece allow the inspector to utilize the eddy current equipment for flaw detection.

Nonferromagnetics

Eddy current examination of nonferromagnetic materials is common. Alloys of aluminum, titanium, copper and nickel are inspected regularly in aerospace, power generation, chemical and petrochemical applications. Good candidates for eddy current testing include aircraft components and steam generator/chiller tubes. Eddy current examination is also used for alloy sorting, hardness testing, corrosion detection and coating thickness evaluation.

Magnetic permeability of nonferromagnetic materials is assumed to be constant, allowing one to accurately perform phase analysis calculations. These calculations allow the technician to accurately determine inspection parameters such as coil impedance, phase angle and eddy current penetration depth. The eddy current probe's test frequency, the magnetic permeability of the test material and its electrical conductivity values are characteristics affecting the density of the eddy currents throughout the test part. Eddy currents are more dense near the test coil.

This concentration of eddy currents at the test piece surface is defined as the "skin effect." As the eddy currents are generated in the test specimen, the current density decreases exponentially. One standard depth of penetration is defined as the depth at which the eddy currents entering the test piece are reduced to approximately 37% of those at the surface (Fig. 2). The formula for one standard depth of penetration is

$$\delta = 1.98 \sqrt{[\rho/(f^*\mu_r)]}$$

For air and nonmagnetic materials the magnetic permeability is constant (see Table 2). Therefore,

$$\delta = 1.98 \sqrt{(\rho/f)}.$$

Inductive reactance is the opposition, independent of resistance, of a coil to the flow of alternating current. By using the formula for inductive reactance (assuming the reactive component is imaginary), $X_L = 2\pi^* f^* L$, and the given resistance for the test piece (assuming the resistive component is real), a phase diagram, such as the one shown in Table 2, can be constructed.

From the phase diagram (impedance graph), the coil's initial impedance and phase lag can be calculated.

$$Z = \sqrt{(X_L)^2 + (R)^2}$$

$$\theta = \text{Arctan}\,(X_L/R)$$

The difference in eddy current densities from the surface to the interior of the test material is known as phase lag. After performing these calculations, the inspector can be aware of all of the parameters and can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accurately perform the examination on nonferromagnetic materials. Knowing the exact location of the eddy currents is crucial when performing an examination on steam generator/chiller tubes.

Ferromagnetics

Ferromagnetic materials have long been considered "off limits" to eddy current examination because of random magnetic permeability changes. These permeability variances in ferromagnetic materials make ordinary phase analysis difficult unless the material is magnetically saturated. Without saturation, permeability variances could create signals that mask discontinuity signals.

Magnetization theory states that permeability can be made relatively constant by saturating the material with an independent magnetizing force. If the test piece is completely saturated, magnetic permeability can be considered constant. This would allow for phase analysis calculations and an accurate eddy current examination. The inability to completely saturate large ferromagnetic components and then demagnetize them after the examination is a major reason why eddy current examination technologies have not been aggressively utilized for ferromagnetic materials—especially for field applications in the gear industry.

Eddy current examination of ferrous materials is also known as magneto-inductive testing. This type of NDE uses the induced electric current as the source of the magnetic field. For the gear examination procedure, only the induced currents at or near the surface are interpreted.

Electromagnetic techniques are most sensitive to the test material variables nearest the test coil due to the "skin effect." The "skin effect" is the product of the mutual interaction of the eddy currents, the selected test frequency, the test material's electrical conductivity and its magnetic permeability. Changes in coil impedance created by surface (and slightly sub-surface) flaws in the vicinity of the eddy current probe are detected and displayed on the eddy current CRT. Unlike the case with tubing applications, where interior defects are scrutinized, little attention is devoted to internal discontinuities. Magnetic permeability variances are still a difficulty, but they are dramatically reduced by the effective utilization of the "skin effect" phenomenon. Since the inspection is magneto-inductive (the magnetic field is derived from induced electrical current), no residual magnetic fields remain once the examination is completed.

Development

During the late 1980s, Steven W. Pogue, an NDE lab manager, developed the eddy current gear examination system to inspect large diameter, open lubricant gears. These gears were in service on large capacity draglines and stripping shovels in the surface mining industry. Mine personnel wanted to establish a quantitative NDE technique without sacrificing production. Magnetic particle examination of large gear systems was not feasible. Removal of high-tack open gear lubricant for the sake of an inspection was a chore not readily undertaken by maintenance workers.

Because of the history of the nature and type of actual gear tooth failures, the tooth root area along the entire face width of each tooth and both side edges became the target area for the inspection. Upper flank, pitch point and upper face areas of each tooth were not focused on because of difficulties with wear (pitting, spalling and metal push). Because eddy current technology senses homogeneous changes in the test material near the probe, indications produced by tooth wear conditions would be too numerous to interpret.

In early 1989, improvement in the design of probes allowed them to retain their required sensitivity and be usable in spite of up to .25" of lubrication on the gears. Research and development progressed at local mines, and by the fall of 1989 the system was ready for use.

The eddy current gear examination system for large gears consists of a portable eddy current machine, proprietary scanning probes, various cables, scrapers, cleaner (solvent for initial cleaning and nonchlorinated for final cleaning) and protective clothing. A portable magnetic particle yoke and wet or dry magnetic particles are recommended for flaw verification. This "double sorting" is a common practice in nondestructive examination.

Eddy Current Examination

The procedure begins by removing compacted lubrication from the tooth roots using a root scraper that closely conforms to twice the fillet radius of the gear teeth. Lubrication is also scraped from the face width side edges. The teeth are numbered for documentation and repeatability. If possible, stationary reference points are used for reporting. Then, if they are accessible, the side edges of the teeth are scanned. They are also inspected for flaws extending from tooth roots. It is advisable to follow the contour of the tooth when scanning.

Two types of failure modes exist when fatigue cracks are detected in gear tooth roots. The most common mode attempts to split the gear band. Crack propagation in a tooth-to-tooth pattern (shearing teeth from the band) has also been regularly documented. Following the tooth contour will detect either failure mode.

Once the side edges have been inspected, the tooth root inspection follows. The process begins by selecting the proper size root scan probe. It is important to choose a probe diameter that closely matches the fillet radius of the gear teeth. If the proper size probe is not available, multiple passes through the tooth root, paying close attention to the flank/root junction areas of each tooth, are recommended.

The scanning takes place by moving the probe at a controlled pace throughout the entire face width of the root being scanned (see Fig. 3). If the remaining lubricant in the roots is very tacky, commercial lubricant is applied in the roots to help move the probe. At least two passes through the root are made to insure proper coverage. If no indications (electronic signals that point to

Fig. 3 — An NDE technician uses a probe with a proprietary design to perform an eddy current examination (tooth root scan) of a large grinding mill ring gear.

Fig. 4 — Tooth root cracks (shown in red and circled in white) documented in the roots of two adjacent teeth. Cracks were detected with eddy current testing and double sorted with dry magnetic particle examination (red color). Note undisturbed lubrication condition in the tooth roots of gear teeth that passed the eddy current examination.

Fig. 5 — An NDE technician performs a side face scan of a small gear. An indication signal is displayed on the eddy current instrument (triggering the need for further evaluation; i.e., "double sorting").

the existence of flaws) appear on the eddy current instrument, the inspection proceeds to the next tooth root. The examination ends when all accessible tooth roots have been inspected.

When a phase shift indication appears on the eddy current instrument CRT (see Fig. 4), the inspection is halted for indication evaluation. The defect area is pinpointed using communication between the technician running the probe and the technician interpreting the instrument. The precise area is cleaned using solvents and scanned again. If the indication disappears, the inspection continues.

The disappearing indication phenomenon is usually caused by metal flake compacted in the remaining lubrication. The eddy current instrument senses a change in magnetic permeability created by the metal flake and produces an indication signal. If the indication remains after reexamination, further evaluation is necessary. The suspected area is cleaned using a commercial, nonchlorinated cleaner, and a magnetic particle examination is performed. Indication areas are documented (see Fig. 5). Shear (transverse) wave ultrasonics can sometimes determine the depth of the flaw at the client's request. The defect depth evaluation usually takes place after the eddy current examination is completed.

Practical Examinations

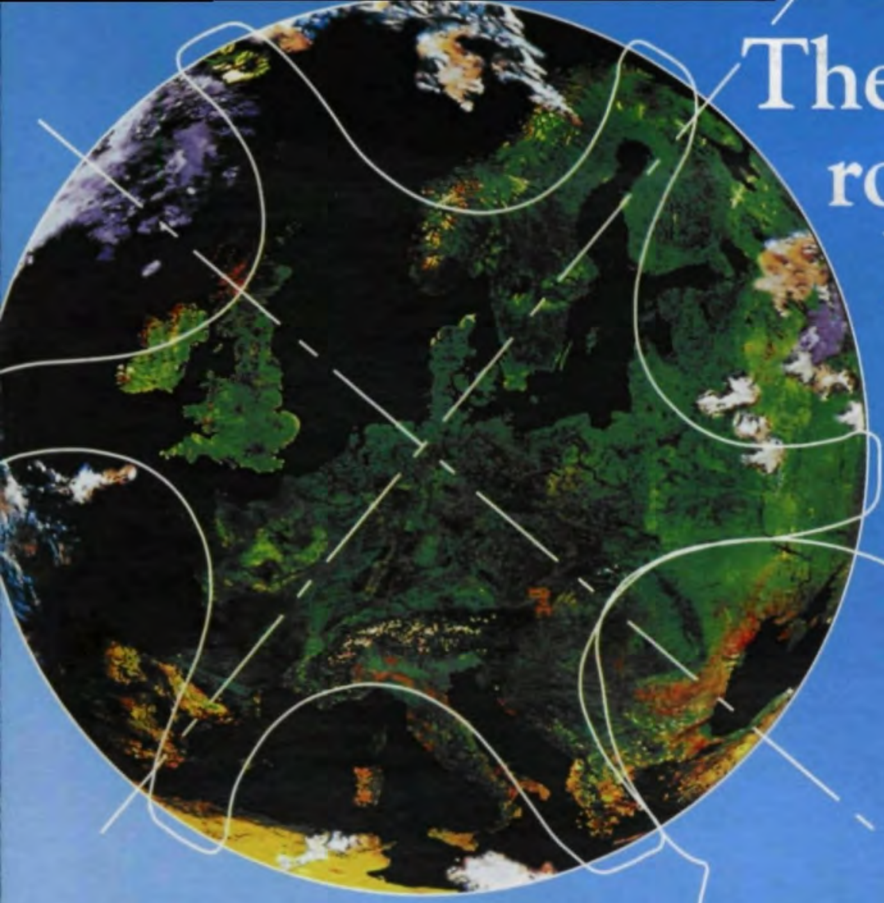
Much initial work in eddy current testing was done on mining equipment. Large open gearing applications (swing racking or bull gears and their corresponding drive pinions, for example) were targeted. Flaws ranging from minor scratches and pits to severe cracks were detected.

In early 1992, the steel and aluminum rolling mill industries began to adopt eddy current techniques. Covers were removed from oil-bathed gearboxes, exposing multiple gears for examination. Indications of flaws have been found in the tooth roots of large bull gears and double-helical, high-speed pinions. Eddy current tests have also been performed in roughing and finishing mill stands, shear drive boxes and vertical edger assemblies. Grinding mill (ball, rod, autogenous and semi-autogenous) and rotary kiln ring gears (spur design) are very similar to the gears found in the mining industry. These are the applications for which the eddy current gear examination system was designed. Findings from these inspections parallel those from other industries.

The Time It Takes

Gear inspection time is directly proportional to the number of indications encountered, depending heavily on the time it takes to clean suspected areas and perform the magnetic particle examination. The inspection pace is very rapid on gears that are in good condition. A large ring gear (four segments, open lubrication, 38' outer diameter, 26.5" face width, and 448 teeth) in service on a semi-autogenous mill was completely examined in eight hours, including time for cleaning all equipment. No significant indications of flaws were detected.

In another case, during one eight-hour shift, a mill



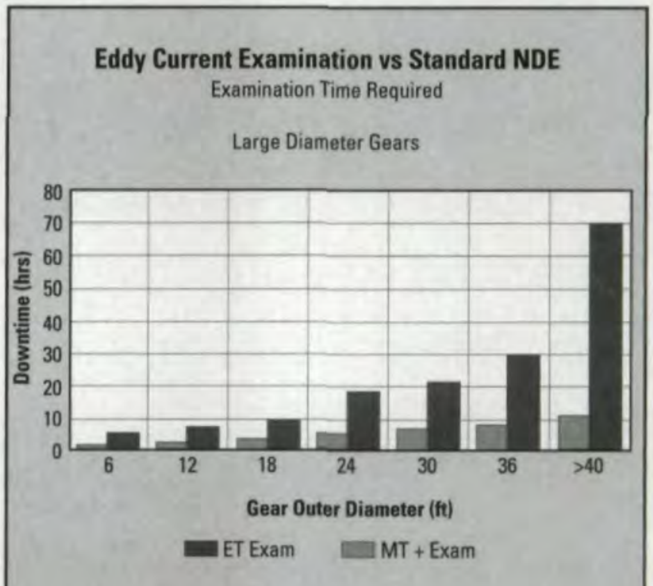
was taken offline, one cover was removed, the gear was inspected (with little help from maintenance personnel) and the cover reinstalled.

Obviously, when flaws are detected, the process takes longer. For example, the inspection of a ring gear installed on a medium size mining shovel (one-piece construction, open lubrication, 19' outer diameter, 13.5" face width and 154 teeth) took approximately 10 hours. But 73 tooth roots contained cracks. Flaw sizes ranged from 0.125" to 8" in length (see Fig. 5).

Conclusion

Based on increased downtime, labor, safety and environmental concerns, standard magnetic particle and/or dye penetrant examinations are usually not completed on large gearing applications to the extent recommended by the manufacturer. By performing an eddy current examination, engineering and maintenance personnel can be aware of potential problems quickly (usually within eight to ten hours). An enormous amount of man-hour savings, coupled with increased production, can be achieved by implementing the eddy current examination technique as shown in Fig. 6.

Upon comparison of nondestructive examination methods (covering the same precise area), eddy current techniques are far superior to magnetic particle and/or dye penetrant methods. The main argument for this is the fact



MT+ = time involved for magnetic particle/dye penetrant examination (standard NDE) and pre-clean time.

All values are based on field experience and maintenance information.

Assumptions: Gears are in good condition (no metal flake in roots and/or severe wear).
Few flaws detected per method.
Adequate assistance from maintenance personnel (gear movement/cover removal).

Fig. 6 — Comparison of required time for eddy current examination and standard NDE.

that the potential for human error is greater using the magnetic particle and/or dye penetrant techniques. Less reliance on component cleaning, lighting conditions and eyesight make eddy current testing the more dependable examination method. Because of the localized scan design of the eddy current system and the wide coverage areas (tooth faces) of the other methods, accurate examination method comparisons could not be completed for an entire gear.

For production and maintenance planning staffs with adequate resources, the new eddy current and standard NDE methods work well together. An effective use of eddy current and magnetic particle examination technologies provides for excellent preventive maintenance. An eddy current examination on an annual basis will pinpoint potentially harmful discontinuities at the earliest point in time. A 100% tooth profile magnetic particle/dye penetrant examination should be performed at five-year intervals to check for tooth wear and profile flaws.

Because of demands for increased production and the downtime required to perform standard NDE techniques, gear examinations are frequently performed inadequately or not at all. For maintenance and engineering personnel worried about the downtime needed for a gear inspection, the eddy current gear examination system quickly eliminates doubts whether a potentially harmful condition exists in a particular gearing application. ○

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Christopher E. Collins
is a mechanical engineer with Ultron Incorporated, a nondestructive testing service and consulting company in Mt. Vernon, IL.

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