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AN EDDY-CURRENT DISTANCE GAGE FOR
PRECISE STATIC MEASUREMENTS

J. F. Ellis

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the ATOMIC ENERGY COMMISSION under U. S. GOVERNMENT Contract W-7405 eng 26

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ABSTRACT

An eddy-current gage for proximity measurements has been designed which employs a self-contained, high-stability, inductance-capacitance oscillator to produce an output signal whose frequency is related to the separation between a resonant coil and a conducting surface. A typical 5/8-inch-diameter probe can resolve a mechanical displacement of one microinch at a separation of 40 mils, and a typical two-inch probe will resolve a displacement of 50 microinches at a separation of one inch. The device is insensitive to dielectric materials and is useful for a variety of gaging applications including those performed under oil or water.

CONTENTS

SUMMARY	7
INTRODUCTION	8
EDDY-CURRENT FREQUENCY-SHIFT PROXIMITY GAGE	11
Background	11
Theory of Operation	11
Construction	13
Performance	14
Special Applications	18
REFERENCES	22
APPENDIX	23
Typical Response Curves	23

SUMMARY

Eddy-current distance gages usually operate by exciting a coil at some frequency between 100 kHz and 2 MHz, and determine the separation between the coil and a conducting surface by measuring the impedance of the coil. For maximum precision, development of this eddy-current distance gage departs from any attempt to measure coil impedance, and relies completely on the precise measurement of the resonant frequency of the sensing coil when it is used in combination with a stable capacitor and oscillator. This technique allows the output to appear in direct digital form, and provides marked improvement in the resolution and accuracy of static measurements. By using a seven-digit frequency counter, mechanical displacements as small as one microinch can be observed.

INTRODUCTION

The primary objective of this development program was to provide a portable means for accurately measuring the thickness of a large-area composite material having a nonmagnetic metal substrate. Because of the area involved, conventional mechanical methods could not be used. Radiography had been used for these measurements, but the equipment was not portable and the process was too time consuming to enable readings to be taken during the fabrication process. Ultrasonic techniques could not be used because of variations in the density of the material. It was, therefore, necessary to employ some form of one-sided electrical "noncontact" distance gaging that would respond to the metal substrate but not to the composite. (The gage would rest against the composite's outer surface and measure the distance to the substrate.)

A secondary objective of the study was to provide a general-applications, close-proximity gage having improved accuracy and a digital readout.

An electrical close-proximity (lift-off) gage may belong to one of several types, including those employing a spark gap, magnetic induction, capacitance, or eddy current. The basic principles of these types are as follows:

1. Spark-gap gages determine very short separation distances by the voltage required to break across a gap in a known atmosphere.
2. Magnetic induction gages measure the reluctance of an external field path and relate it to the separation between a set of magnetic terminals and some magnetic surface.
3. Capacitance gaging involves the determination of electrical capacitance between an electrode and some conducting surface. It requires that the dielectric constant of the separating medium be known in order to express this capacitance in terms of distance.
4. Devices measuring lift off by eddy currents are similar to magnetic induction gages in the sense that they are electromagnetic, but their use of high-frequency excitations eliminates the need for a magnetic substrate or surface. An alternating current flowing in an inductor produces an alternating magnetic field corresponding to the magnitude of the current, but at right angles to it. It is common knowledge that such a current produces an axial field within a coil, and that a conducting object in this field will have a current induced in it. If the object has a relatively large surface area, these induced currents will flow in "short-circuited" circular paths

that will "couple" back to the exciting coil and effectively lower its impedance. As the frequency of the current is increased, the depth to which these circulating (eddy) currents will penetrate the material decreases. Using frequencies generally ranging from 100 kHz to 2 MHz, the separation between a driven coil and the surface of a good conductor can be measured as a function of the change in coil impedance.

Spark-gap and magnetic induction gages are not suited for measuring composite layers on a nonmagnetic substrate. Capacitance gages can measure lift off to a high degree of accuracy provided they are used within their range and with suitable materials. Although normally used to measure distances in air, they can measure through other materials provided the dielectric constant is known and remains uniform. However, because of variations in density it was not possible to accurately determine the dielectric constant of the composite material to be measured, or to calibrate a capacitance gage to it.

Eddy-current techniques were selected for the required measurements because of their primary reliance on inductive mechanisms that can be made very insensitive to changes in stray capacitance. Eddy-current distance gages often incorporate the sensing coil into one arm of a bridge circuit which is sensitive to changes of inductance, impedance, phase, or some combination of these.⁽¹⁾ Other systems use the sensing element as the tank coil of a critically damped oscillator. Reduction of the coil's effective impedance (by eddy-current reflected energy) causes the amplitude of the oscillator's output to vary in a manner that is almost proportional to the coil's spacing from the test part. Another eddy-current distance gage uses a carrier of 30 MHz or higher to drive the primary of a three-coil, r-f transformer which serves as the detector. The coils are aligned axially, with the primary in the center. The distance to a conducting surface is measured by the differential output of the two secondary coils. The major advantage of this system is its very fast response and its ability to perform in electrically hostile environments.⁽²⁾

Many variations of the basic concepts of eddy-current testing have been devised, and a number of them have been patented. As a general rule, most of these devices rely on the measurement of phase and amplitude; and, therefore, are by nature somewhat imprecise. Because of these limitations, a new method was developed that offered greater precision and a direct digital output.

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EDDY-CURRENT FREQUENCY-SHIFT PROXIMITY GAGE

BACKGROUND

During 1926, Herman E. Kranz filed for a patent on a device that measured the thickness of metals by the use of induced eddy currents.⁽³⁾ The circuit was a simple vacuum-tube oscillator having an extra coil in the grid loop acting as a detector, and a meter in the plate circuit showing the relative energy used by the oscillator. While Kranz' patent neither recognized frequency shift nor made any provision for its detection, it appears now that a frequency change would have occurred when the detector coil came near the test part.

Later, in 1945, Jacob E. Dinger disclosed a circuit that determined the resonant frequency of an eddy-current detector by comparing its output to that of a variable reference oscillator.⁽⁴⁾ The problem with this circuit was the fact that the vacuum-tube oscillators had to be located remotely from the probe, and handling of the instrument would create spurious frequency shifts due to changes in cable capacitance. It also required manual "hunting" for the resonant frequency.

THEORY OF OPERATION

The resonant frequency of an inductance-capacitance (LC) circuit having a moderately high Q may be expressed as:

$$F = \frac{1}{2\pi\sqrt{LC}} ,$$

where:

F represents the frequency in hertz,

L the inductance in henrys, and

C the capacitance in farads.

Instead of driving a coil with a fixed-frequency, fixed-amplitude, r-f current and measuring its impedance with a bridge arrangement, the new gage makes the detector coil the primary inductive component of its oscillator. A reduction of the coil's impedance raises the frequency of the oscillator just as it did in Dinger's circuit. However, unlike Dinger's oscillator, the new configuration has the active portion of the oscillator self contained in the probe. Since the

accuracy of the gage depends directly on the frequency repeatability of the oscillator, an effort has been made to construct a highly stable oscillator having a minimum number of components.

Figure 1 presents a simplified diagram of the new gage. In free space, the resonant frequency of LC_1 may range from one to ten MHz, depending on the size and design of a given probe. When a conducting surface, S , appears in the field of Coil L , reflected energy from the induced-surface eddy currents causes the oscillator's frequency to increase. The switching action of Q_1 produces a series of pulses corresponding in number to the oscillator frequency. These pulses appear on the common input-output cable and are counted for a preset time by the frequency counter. The resulting number corresponds to a given separation distance between L and S . Since the oscillator's frequency decreases asymptotically with increasing separation, it is necessary to plot the relationship of frequency to distance for each probe.

The advantages of measuring separation and thickness by frequency shift relate to the fact that a given frequency can be measured to a greater accuracy than can a given amplitude or phase angle. Probes can be built having self-contained oscillators that are quite stable. Their degree of frequency shift is primarily determined by their geometry relative to the part in question. Precision frequency counters are now available at reasonable cost, giving the system definite advantages for computer interfacing because of its direct-digital (rather than analog) output. The ultimate resolution of the gage is limited by the random fluctuations of the oscillator and the resolution of the counter. The effects of temperature can be measured and accounted for.

Figure 1. ELECTRICAL CIRCUIT OF THE EDDY-CURRENT GAGE.

CONSTRUCTION

The first of the new eddy-current frequency-shift gages to be built was a composite probe comprising a 3/4-inch-diameter cylinder of micarta having a circular groove cut near one end and a coil wound therein. It was designed specifically for thickness measurement by placing it against the surface of the material to be measured. Figure 2 is a drawing of this probe having a self-contained oscillator potted in epoxy. Its characteristics are as follows:

Design Range	0 to 125 mils
Frequency in Free Space	1.56 MHz
Frequency on Contact (flat aluminum)	1.84 MHz
Sensitivity at a One-Mil Distance	5,040 Hz/mil
Sensitivity at a 125-Mil Distance	65 Hz/mil
Maximum Useful Range	200 mils
Temperature Coefficient	- 100 Hz/ $^{\circ}$ F (- 64 ppm/ $^{\circ}$ F)
Normal Supply Voltage	3 volts (battery)
Random Frequency Variations	7 Hz (maximum)

Since the relative geometry of the coil and the gaged surface determine the sensitivity of the probe, its operating range may be considered as equal to the radius of the coil, but useful measurements can be made at twice this distance if extra care is exercised. Mechanical stability of the coil is of primary importance. Thermal expansion of the coil is the largest single contributor to the oscillator's temperature coefficient. Due to the high thermal

Figure 2. FIRST FREQUENCY-SHIFT PROXIMITY PROBE.

coefficient of expansion of the composite materials used for the housing and internal potting of this first prototype, its temperature coefficient was high compared to later units using Pyrex glass forms.

Figure 3 gives a view of a later unit. This 2.5-inch-diameter probe has an intended useful range extending from zero to 1.5 inches. Additional refinements were made to insure accuracy and increased range. Flanged Pyrex tubing was chosen for the form housing because of its low thermal expansion, the relative ease with which it could be worked, and the fact that it was available in all the desired sizes. The coil is wound in the annular groove and bonded to the glass with epoxy to insure its overall mechanical integrity. Figure 4 presents a schematic diagram of the circuit. When the switch, S_w , is closed, the circuit through the oscillator via the coaxial cable and $R_2 - R_3$ is completed. Transistor Q_1 is biased so that the oscillator will operate at a very low power level. The inductor, L_1 , is center tapped with the halves A and B tightly coupled and wound as a single annular coil. The 2.5-inch probes have four-turn coils of Size 26 magnet wire. Smaller ones may be wound with closely spaced bare wire of Size 36 or smaller. This technique is further explained later in this report (SPECIAL APPLICATIONS).

By connecting the coaxial line to the oscillator at the center tap of L_1 , any direct coupling between the line and the tank circuit (L_1, C_1, C_2, C_3, C_4) is minimized. Radio-frequency pulses are fed back into the line only when Q_1 is conducting. Capacitor C_x is selected for further decoupling. The low-level pulse train appearing on the coaxial line is now amplified by Q_2 and is sufficient to drive a standard frequency counter. Capacitor C_1 is selected for rough tuning while C_4 is for fine tuning. Temperature compensation is provided by C_2 and C_3 . All components must have the best possible stability.

A set of five probes having diameters ranging from 2.5 inches to 0.2 inch has been built to cover a variety of inspection applications. The three large probes (shown in Figure 5 with their associated power supply and counter) are fitted with adjustable pedestals to enable them to measure the height of a given point above some general reference plane (see Figures 6 and 7). The pedestal may be extended to hold the probe slightly elevated by some predetermined amount, or it may be retracted to permit direct seating of the rim. The pedestal probes are also fitted with ringed tripod fixtures to hold them normal to the surfaces on which they are placed. The Pyrex tubes may slide freely for a short distance within the fixture to insure that the spacing is relative to the pedestal and not the tripod.

PERFORMANCE

There are some obvious precautions that must be taken if the best results are to be obtained. It must be remembered that the probe "sees" the entire

Figure 3. PROBE WITH TRIPOD.

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Figure 4. ELECTRICAL CIRCUITS FOR THE PROBE AND PREAMPLIFIER.

area under it. For this reason, it must be calibrated to the particular geometry it is to measure, and must be handled in such a way that no uneven heating will result. Metallic objects other than the test part must be kept away.

Another precaution that may or may not be so obvious is that the system must not be used near strong electromagnetic fields that radiate energy within its

Figure 5. THICKNESS PROBES AND FREQUENCY COUNTER.

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Figure 6. PROBE FACE SHOWING THE PEDESTAL.

operating frequency range. Because of the low power levels used, it is possible for the inductor to act as a miniature loop antenna causing the oscillator to be pulled into frequency lock with the external field. Fine-structure calibrations indicate that strong r-f fields outside the system's deviation band, or on-frequency signals from distant transmitters, have no measurable effect.

Table 1 summarizes some typical performance characteristics of five different probe types that have been built so far.

Due to the low power consumption of the system (about six milliwatts for the 2.5-inch probe) there is very little heating; and, for all practical purposes, the probes may be considered to follow the ambient temperature. It was discovered that the temperature coefficient of the coil increased after the bonding epoxy was applied. This effect was opposite to that which was first expected, and was attributed to the dielectric temperature coefficient of the epoxy and the mechanical compression of the coil caused by the expanding epoxy confined in the Pyrex groove. Nevertheless, the design was retained because of its rugged mechanical stability.

Figure 7. SPACING ACTION OF THE PEDESTAL.

The ultimate resolution and accuracy which can be obtained with this system was tested by placing a 2.5-inch probe in a controlled environment where the temperature was maintained at 68 ± 0.05 degrees Fahrenheit. The probe was

Table 1
TYPICAL PERFORMANCE CHARACTERISTICS OF EXISTING PROBES

	Probe Diameter				
	2.5 Inches ⁽¹⁾	2.0 Inches ⁽¹⁾	1.5 Inches ⁽¹⁾	0.625 Inch ⁽²⁾	0.2 Inch ⁽³⁾
Intended Range (in)	1.5	1.0	0.75	0.10	0.10
Useful Range (in)	2.0	1.5	1.0	0.35	0.30
Free-Space Frequency (MHz)	2.37	3.38	2.7	5.4	4.12
Frequency on Contact with Aluminum (MHz)	2.96	4.16	3.24	6.84	5.14
Sensitivity at 50 Mills (Hz/mil)	1,020	2,600	2,300	8,700	5,700
Sensitivity at 500 Mills (Hz/mil)	280	300	140	-	-
Temperature Coefficient Compensated (Hz/°F)	5	3.2	1.9	1.7	38.3
Temperature Coefficient Uncompensated (Hz/°F)	-	128	109	102	260
Maximum Frequency Variations During 10-Minute Period (Hz)	0.3 ⁽⁴⁾	2.0	0.8	3.1	2.3

(1) Probe made of Pyrex with pedestal and tripod. Used as a thickness gage.

(2) Probe made of Pyrex with an open end. Used as a proximity gage.

(3) Probe has a ferrite core. Used as either a thickness or proximity gage.

(4) Controlled-environment test described in text.

left turned on and was not disturbed for 24 hours, after which it was placed in an insulated box to shield it from the operator's body heat. After another brief stabilizing period, the frequency was monitored with a frequency counter. Random deviations were ± 0.15 Hz at a fundamental frequency of 2.3 MHz. The total frequency drift over a one-hour period was 0.7 Hz and represented a maximum attainable accuracy of 0.3 microinch at a distance of ten mils, or about 32 microinches at 1.5 inches. In normal use, these tightly controlled conditions cannot be met, and the accuracy of the gage will be degraded by at least an order of magnitude.

Each probe is calibrated by securing a sample of the material it will gage and moving the probe in precise increments with the aid of a micrometer slide positioner. A plot or table can then be made showing the response of a given probe. When measurements are to be made on a layer of dielectric material, it is assumed that the indicated thickness will be the same for the material as it was during calibration in air. To verify the insensitivity of the probe to a dielectric, a metal plate was placed slightly more than one inch from a 2.5-inch probe, and a reading was taken. A one-inch-thick micarta slab was then placed between the probe and plate and another reading was taken. An equivalent error of 0.7 mil was thus produced. (This error diminishes rapidly at lesser thicknesses due to the increased flux coupling to the substrate.)

SPECIAL APPLICATIONS

Figure 8 provides a view of the 0.625-inch-diameter probe designed for placement in the tool holder of a machine to monitor the runout of its spindle and faceplate. This probe has a sensitivity of 10 Hz per microinch when spaced 41 mils away from the rotating member. A 3/8-inch-diameter probe was constructed similar to the one shown in Figure 8 and was used for evaluation purposes. Tests showed that any of these probes would perform well under oil or water if their ends were properly sealed.

The previous method of winding the coil in a groove did not yield the desired stability in the smaller probes. Compression and slippage of the wire's enamel covering was sufficient to produce measurable frequency shifts. A satisfactory solution was to wind a single-layer coil of bare wire on a ground-glass or fused-quartz surface, carefully spacing the turns with the aid of a microscope. Tightly stressing the wire as it was wound, and cementing it afterwards, produced a coil of excellent thermal and mechanical stability.

Figure 9 is a photograph of a 0.2-inch-diameter "breadboard" core assembly and circuit board of a probe to be used in a specialized machining operation. To increase the range of this small probe, a powdered iron core is used instead of a Pyrex or quartz rod. It appears now that the large probes are best made

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Figure 8. PROBE ADAPTED FOR INSPECTION OF A ROTATING MACHINE.

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Figure 9. TWO-TENTHS-INCH-DIAMETER CORE ASSEMBLY FOR A SHIELDED PROBE.

using air-core forms of Pyrex, ceramic, or fused quartz, while the small ones appear to give the best all-around performance if wound on powdered iron slugs.

The 0.2-inch-diameter probe when assembled is seen in Figure 10. The interchangeable base plates shown in the photograph enable it to be used in contact with flat, cylindrical, or spherical surfaces for coating-thickness measurements. Since the probe's body is a cylinder contained inside a larger concentric cylinder, its longitudinal slide motion enables the center core to touch the measured surface while the baseplate holds the device normal to the part. This probe design is easily adapted to noncontact proximity measurements by removing the guide screw and sliding the probe all the way out of the fixture. It can then be clamped in any suitable mount.

A set of typical response curves is given in the Appendix.

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Figure 10. SHIELDED PROBE AND BASE PLATES.

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- (3) Kranz, H. E.; US Patent 1,815,717; Filed January 12, 1926, Granted July 21, 1931.
- (4) Dinger, J. E.; US Patent 2,581,394; Filed August 20, 1945, Granted January 8, 1952.

APPENDIX

TYPICAL RESPONSE CURVES

Figure A-1. TYPICAL RESPONSE CURVE OF A 2.5-INCH PROBE TO AN ALUMINUM SURFACE WHEN THE PEDESTAL IS EXTENDED FOR SUPPORT.

Figure A-2. TYPICAL RESPONSE OF A 0.625-INCH PROBE TO STEEL AND ALUMINUM.

Figure A-3. TYPICAL RESPONSE OF A 0.2-INCH PROBE WHEN CONTAINED IN A BRASS CYLINDER. (Test Material is Aluminum)

Figure A-4. FREQUENCY STABILITY OF A TWO-INCH PROBE WITH A PEDESTAL. (Probe F 2.0-2; 74.4° F)

Figure A-5. TYPICAL FREQUENCY STABILITY OF A 1.5-INCH-DIAMETER PROBE WITH A PEDESTAL.

Figure A-6. TYPICAL FREQUENCY STABILITY OF A 0.625-INCH-DIAMETER PROBE. (75° F)

Figure A-7. TYPICAL FREQUENCY STABILITY OF A 0.2-INCH-DIAMETER PROBE WITH A POWDERED IRON CORE. (74.4° F)