# KAMAN

Measuring and Memory Systems
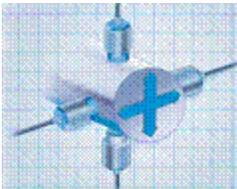
DISPLACEMENT robot repeatability | valve position | artificial heart diaphragm position | servo positioning | disc drive head flying height | oil film thickness | robotic welding servo position feedback | pulp paper refiner control feedback | turbine blade tip clearance | fuel injector needle lift | valve bounce | engrave head feedback | molten metal level | structural movement.
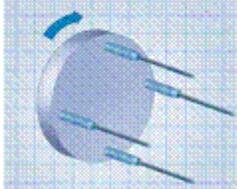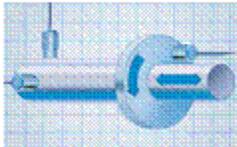
VIBRATION rotating shaft | ultrasonic weld horn | uranium enrichment centrifuge | dental drill | silicon wafer slicing blade | disc drive | transmission coupling | centrifugal pump | loudspeaker cone | gas turbine shaft | structural | servo valve.

ALIGNMENT mirror stabilization | fast steering mirrors | tensile testing | sounding rocket image trackers | seam tracking | magnetic bearing suspension | shaft alignment | mask alignment | parts positioning | sheet metal edge detection | die and ram alignment.

DIMENSIONING thickness | OD | ID | concentricity | straightness | flatness | insulation thickness | printer in cartridge foam thickness | copper clad PCB thickness | strip steel thickness.

SORTING multiple category sorting | metallic parts gauging | in-cage ball bearing presence | ceramic capacitor position | drill bit diameter sorting | multiple strand wire inspection.
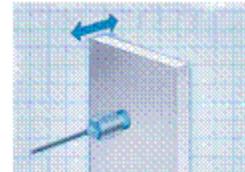
INDUCTIVE TECHNOLOGY HANDBOOK

KAMAN PRECISION PRODUCTS / MEASURING

A Division of Kaman Aerospace

Kaman Precision Products / Measuring is a division of Kaman Aerospace Corporation. Kaman Corporation has over 60 years experience as a leader in aerospace, industrial, military, and consumer products. Kaman Precision Products / Measuring draws on over 40 years of experience with inductive position measurement techniques to bring you the best in advanced sensor technology and signal conditioning electronics.

Our Location

Our Sales Office is located in Colorado Springs, Colorado and our Manufacturing Facility is located in Middletown, Connecticut. We have sales representatives throughout the United States and distributors in countries around the world. We can be contacted in Colorado Springs by telephone at 800-552-6267; by e-mail measuring@kamansensors.com. See our website www.kamansensors.com for a current list of our representatives and distributors with their contact information

TABLE OF CONTENTS

Section 1 - Introduction

Numerous textbooks, handbooks, and assorted publications are available on sensor technology. These documents typically cover a broad range of sensors and technologies, but have limited information on each type. Information on inductive sensors can be found in many of them. This handbook is different in that it condenses technical and application information on inductive sensors into a single source. The intent is to help the reader understand where inductive sensors can be utilized, how to best apply them, and to understand their performance.

Why Kaman?
- Kaman Precision Products has over 40 years of experience designing, testing, and manufacturing non contact inductive measuring systems.
- We have multiple types of inductive technologies and the applications engineering experience to help you choose the best product for your application.
- Custom designed measurement systems are our specialty.
- Standard and OEM measuring systems are available.
- Our standard resolution is 1 part in 10,000 and we are capable of resolution up to 1 part in 100,000.
- Frequency response is electronics dependent and ranges from 10 KHz to 50 KHz.
- Sensors are capable of operating in temperatures from cryogenic to 1100° F.
- Inductive technology is generally unaffected by contaminants such as dirt, oil, grease, water, radiation, and stray RF or magnetic fields.
- Worldwide network of Distributors and Sales Representatives.

We are the "high-end" guys in the inductive world! When you have a demanding measurement application, call your Kaman Applications Engineer…that's Kaman, pronounced "Ca'•man."

Section 2 - Non Contact Measuring Technologies

There are many instruments to measure position, distance, or vibration of an object. These can be segregated into two basic categories: contact and non contact.

Popular contact methods are: Linear Encoders, String Potentiometers, and Linear Variable Displacement Transducers (LVDTs). Some of the benefits of contact measuring systems are: long measuring range, target material insensitivity, a small spot (measuring area) size, and generally lower cost.

While contact instruments are suitable for many applications, they have a limited frequency response and can interfere with the dynamics of the object being measured. Where these factors are a concern, non contact methods have advantages. Below is a list of several types of non contact measuring technologies with some of their features.

Air Gauging: This technique uses air pressure and flow to measure dimensions or inspect parts. These devices operate on changes in pressure and flow rates to make a measurement. A clean air supply is required.   It is acceptable for use on most target materials and typically used for small measuring ranges of 0.010 to 0.200 inches in production environments.

Hall Effect: This sensor varies its output voltage in response to changes in magnetic field. With a known magnetic field, distance can be determined. A magnetic target or attachment of a magnet to the target is required. These sensors are generally inexpensive and are used in consumer equipment and industrial applications. They are also commonly used in automotive timing applications.

Ultrasonic: Ultrasonic sensors operate on a principle similar to sonar by interpreting echoes of sound waves reflecting off a target. A high frequency sound wave is generated by the sensor and directed toward the target. By calculating the time interval between the sent and received signals, distance to the target is determined. Ultrasonic sensors have long measuring ranges and can be used with many target materials, including liquids. Performance is affected by shape and density of the target material. They have lower resolution than most other non contact technologies and cannot work in a vacuum. Ultrasonic sensors are frequently used to measure liquid level in tanks and in factory automation and process industries.

Photonic: Photonic sensors use glass fibers to transmit light to and from target surfaces. Displacement is determined by detecting the intensity of the reflected light. These sensors have a very small spot size and can be used to detect small targets. They can be used with most target materials and in hostile environments. They are also insensitive to interference from EMI or high voltages. Photonic sensors are generally used for small measuring ranges and can have high resolution and frequency response. But, they are sensitive to environmental contaminants and target finish variations.

Capacitance: These sensors work on the principal of capacitance changes between the sensor and target to determine distance. They can be used with all conductive target materials and are not sensitive to material changes. Capacitive sensors have a relatively small spot size and are not sensitive to material thickness, but typically require a target grounded to the measuring system. They can be constructed of very high temperature materials for measurements up to 1200 $^{\circ}$C. These sensors have a small measuring range to sensor diameter ratio and are sensitive to environmental changes and contamination.

Laser Triangulation: These sensors work by projecting a beam of light onto the target and calculating distance by determining where the reflected light falls on a detector. They can measure longer ranges than other non contact technologies; can be used with most target materials, and have a very small measuring spot size. They tend to be the most expensive type of non contact sensor. Measurement is affected by environmental contamination and surface finish variations of the target.

Inductive Eddy Current: Inductive eddy current sensors operate by generating a high frequency electro-magnetic field about the sensor coil which induces eddy currents in a target material. A conductive target is required, but a ground connection to the measuring system is not necessary. Sensor performance is affected by target material conductivity. Inductive sensors have a large spot size in comparison to other technologies. Performance is affected by temperature changes, but not by environmental contaminants or target finish characteristics. They can operate in a vacuum or in fluids. Non conductive material between the sensor and the target is not detected.   The measuring distance is typically 30-50% of sensor diameter.

As with any device, both contact and non contact measuring technologies have a wide range of performance characteristics ranging from very low (on-off) to very high precision (nanometer resolution), depending on their construction. It is not only necessary to choose the correct technology, but also the correct level of performance for an application.

Section 3 - Inductive Technologies Overview

3.1 Basic Inductive Technology

Inductive technology operates on the principle of impedance variation caused by eddy currents induced in a conductive target by a sensor coil. The sensor coil is excited by a high frequency oscillator. Excitation of the sensor coil generates an electromagnetic field that couples with the target. Signal conditioning electronics sense impedance variation as the gap changes and translates it into a usable displacement signal. This technology is capable of sub-micro inch resolution. Information on the following pages further details how this is done.

Basic inductive measurement technology must first be understood before it can be successfully applied. The operational concept is simple; however, many different parameters can affect system performance. The application of this technology should be approached in a logical step-by-step manner which will insure that all parameters are considered.

An AC current flowing in a coil generates a pulsating electromagnetic field. Placing the coil a nominal distance from an electrically conductive "target" induces a current flow on the surface and within the target. This induced current is called "eddy current". The eddy current produces a secondary magnetic field that opposes and reduces the intensity of the original field. This interaction is called the "coupling effect." The strength of the electromagnetic coupling between the sensor and target depends upon the gap between them. Signal conditioning electronics sense the effects of impedance variations as the gap changes and translate them into a usable displacement signal.
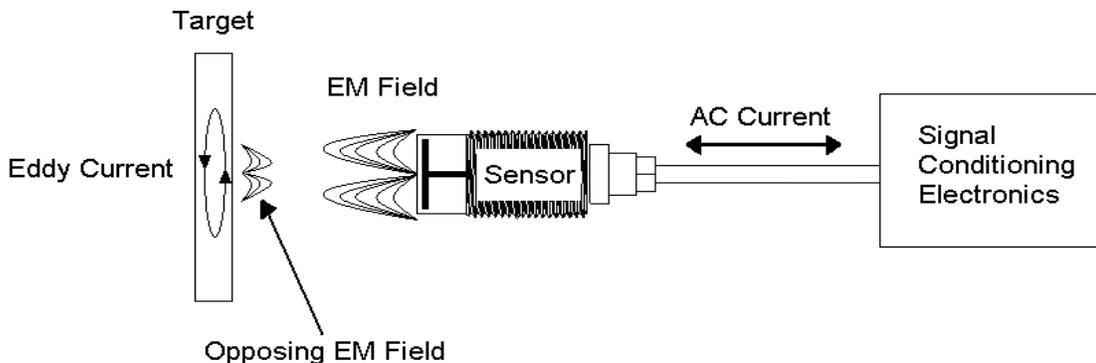
In the previous section, we discussed the basics of how eddy current works in interaction with sensor and target. The following is a discussion of how those eddy currents can be interpreted and processed into useful information in the signal conditioning electronic circuits. There are three popular types of circuits used to process the signal. These are:

COLPITTS CIRCUIT   Single Channel Analog Position
                                                                Measuring Systems

BALANCED BRIDGE CIRCUIT   Single Ended & Differential Analog
                                                                Linear Position Measuring Systems

PHASE CIRCUIT   Single/Multiple Channel Analog High
                                                                Precision Position Systems

Each of these circuits has distinct characteristics. The signal conditioning circuit that performs best in any application should be chosen. Details of each circuit are discussed in the following sections.

3.2 Colpitts Circuit

Theory of Operation

The Colpitts circuit is named after its inventor, Edwin H. Colpitts. This circuit is one of a number of designs using an LC Oscillator and is a very simple and robust. A typical circuit diagram is shown below.
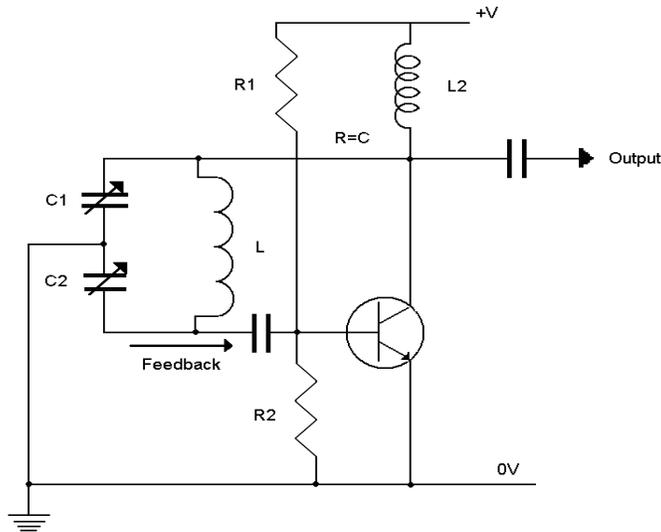
When used as a position measuring device, the sensor coil becomes the inductor in the oscillator circuit. When the sensor coil interacts with a conductive target, the oscillator frequency and amplitude vary in proportion to the target position. This variation is processed into an analog signal proportional to displacement. The basic block diagram of a circuit using this technology is shown below.
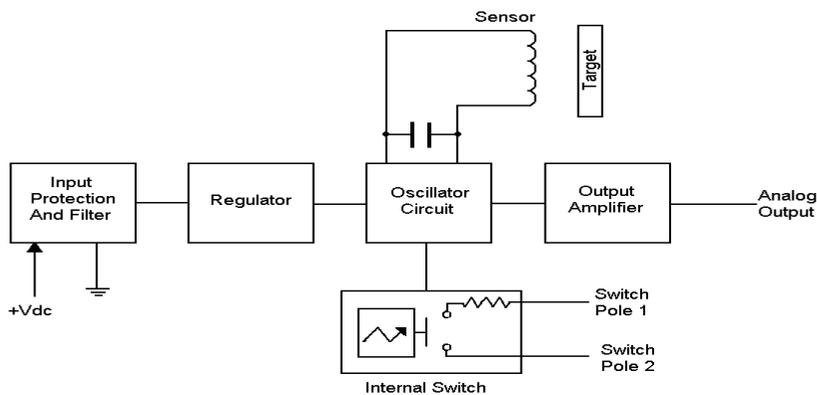
Applications

A Colpitts inductive proximity measuring system is a rugged, low cost, non contact measuring system with good resolution and repeatability for static and dynamic measurements. Output is a non-linear DC voltage signal proportional to the distance between the sensor and the target. A single adjustment for gain control is used to raise or lower the output voltage level to the desired value. This circuit does not have provisions for control of offset or linearity of the output signal.

A Colpitts circuit can be used in a variety of applications with performance quite different from other inductive technologies. This circuit responds to any conductive material, but very well to magnetic steel and highly resistive targets. In general, a Colpitts circuit provides a larger measuring range for the same size sensor than other types of inductive circuits. While output is non-linear over the total range of a sensor, it can be very linear if only a small portion of the range is used in an application and is very repeatable.

Using a Colpitts inductive measuring system, things to consider are:
>   Synchronization of adjacent sensors is not possible
>   System cannot be temperature compensated
>   Limited selection of sensors available
>   Sensor cable length is limited (or circuit will not oscillate)

Typical applications are:
>   Low cost, general purpose measurements where linearity is not required
>   Fuel injector testing
>   Valve lift measurements
>   Shaft or cylinder run out and vibration
>   Small diameter targets which are not detected well by inductive bridge systems
>   Carbon impregnated rubber or plastic targets
>   Wire mesh targets
>   Gear teeth counting
>   Metal forming and stamping
>   Machining and grinding

Systems

Kaman's KD-2446 system is an example of a position measuring system based on Colpitts technology. This system can be used with a variety of sensors and targets with only adjustment of the gain control. Using the adjustable, internal switch feature, this system can be used to directly control external equipment or provide logic voltage levels or alarm signals.

3.3 Balanced Bridge Circuit

Theory of Operation

The Wheatstone bridge circuit was invented by Samuel Hunter Christie in 1833. It was improved and popularized by Sir Charles Wheatstone in 1843 and bears his name to this day. In the inductive bridge circuit, an oscillator excites a Wheatstone bridge. It is a form of a balanced bridge circuit tuned to be near resonance. Slight changes in impedance of the sensor coil, caused by the interaction of the electromagnetic field and the target, will result in big shifts in the output of the bridge.

The target movement causes an impedance change in the sensor coil. This change of impedance in the coil is detected (measured) by the demodulator circuit, linearized by a logarithmic amplifier, and then amplified in the final amplifier stage, which provides offset and gain. This voltage is the system output voltage, provided to the user as an analog voltage directly proportional to target position relative to the sensor.
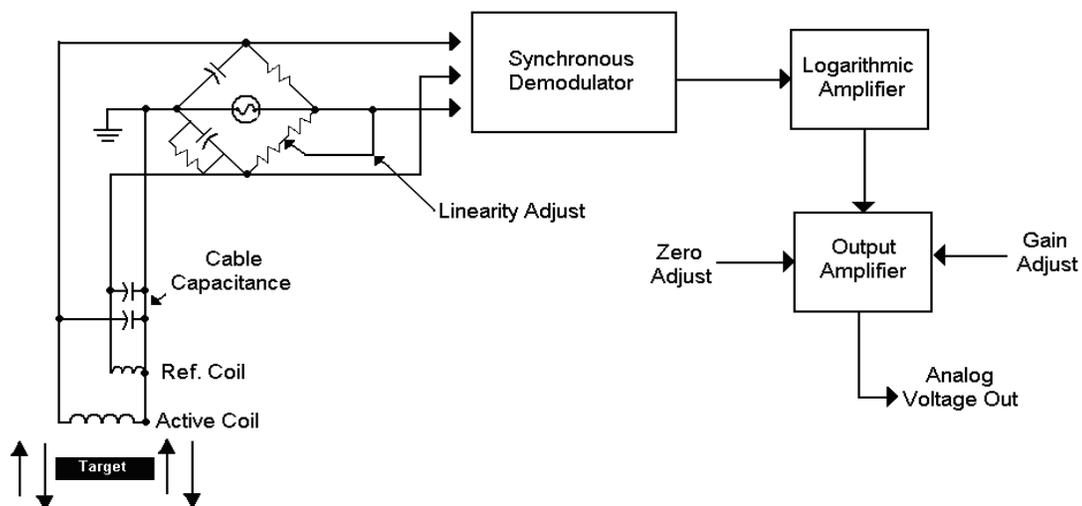
In the single ended configuration, the bridge circuit can be used with both dual and single coil sensors. In the dual coil design, the active and inactive coils are on opposing sides of the bridge. This configuration provides a "canceling" effect which can enhance some performance parameters. In the single coil configuration, only one coil is exposed to the measuring environment. While the impact of the environment may be greater, the stabilization time will be shorter.
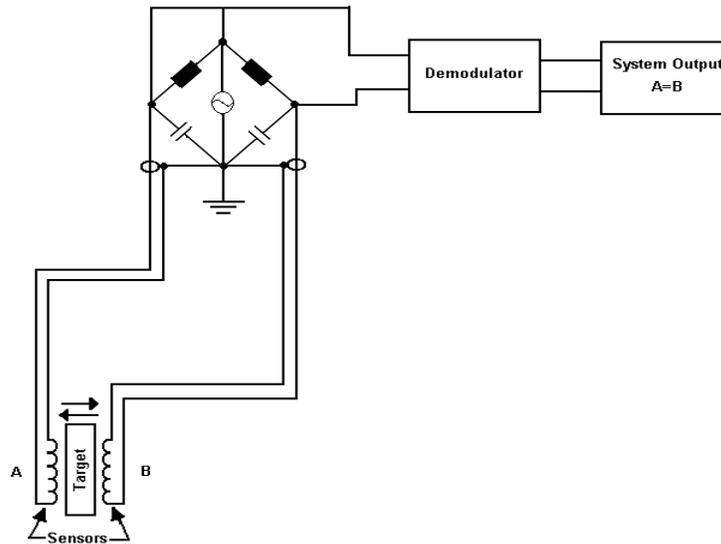
In the differential configuration, two sensors are used to sense target movement. Two single coil sensors are mounted on either side of a target and are connected to opposite sides of the balanced bridge. When the target is electrically centered between the two sensors, the bridge is balanced and system output is zero. This position is called the "null gap". As the target moves toward one sensor and away from the other, the bridge becomes unbalanced and outputs a proportional analog voltage which indicates both the magnitude and direction of movement. This bipolar (A-B) signal is a true differential output. Individual sensor outputs are not available from this type of system.

The differential configuration is more difficult and costly to implement since it requires two sensors for a single measurement. However, compared to a single ended configuration, it does offer some distinct advantages:

- Better temperature stability. Both sensors are equally affected by the same temperature resulting in temperature drift being inherently minimized by the bridge.
- Higher resolution (lower noise) due to simplified circuitry.
- Better long term stability.

When the target is electrically centered between the two sensors at the nominal null gap for each, the system output is zero. As the target moves away from one sensor and toward another, the coupling between each sensor and target is no longer equal; causing an impedance imbalance and its output is amplified, demodulated, and presented as a linear analog signal directly proportional to the target's position. This is a bipolar signal that provides both magnitude and direction of misalignment. Only A-B or differential output is available.

Applications

These single ended systems were developed to satisfy an extremely wide variety of measurement applications for both ferrous and non-ferrous targets, including:

General purpose linear position measurement
Laboratory, research, development, and testing
Metrology
Factory process control
Machine monitoring and control
Shaft run out and vibration where longer sensor cable lengths are required

Applications for differential bridge systems include:

Steering mirror position
Pointing and tracking in night vision and laser systems
Control systems for active vibration monitoring and control systems
Photolithography stage positioning and control
Atomic force microscopy (AFM) stage positioning and control
Satellite based communications and laser pointing systems
Magnetic bearing shaft position and control

Bridge Circuit Systems

Single-ended Systems

The KD-2306 is a single ended, high precision position measuring system. It can be configured with both dual and single coil sensors. There are 3 outputs available: single ended analog voltage, differential analog voltage (not to be confused with differential measurements), and a 4 to 20 mA current output.

The KDM-8206 is a single ended, multi-channel system which utilizes the same basic circuitry as the KD-2306. It is available in one-half, three-fourths, and full 19-inch instrumentation rack configurations of up to 12 measuring channels.

Differential Systems

The KD-5100 is a differential measuring system which was developed to satisfy the demands of high precision military measurement applications. It has a history of use in a variety of high precision/high reliability industrial applications as well.

The DIT-5200 is a lower priced equivalent commercial version of the KD-5100, incorporating COTS (Commercial Off The Shelf) parts in a small commercial electronics enclosure. The DIT-5200 is available with several sensor options suitable for high precision applications. The system provides a DC voltage output. It is intended for low to high volume end user applications and is very well suited to high precision OEM applications.

3.4 Phase Circuit

Theory of Operation

The effects of eddy currents are not only amplitude related, but also phase related. This circuit is based on phase detection as opposed to amplitude detection. Specifically, the phase detection is based on Pulse Width Modulation (PWM) techniques.

Since noise is basically an amplitude sensitive phenomenon, the phase detection technique offers a lower noise floor to begin with. In systems utilizing the amplitude changes, the system is full of op-amps with their inherent noise. The PWM technique used does not require high gain op-amps, which allows for extraordinary low noise on the system output. The proprietary PWM circuit allows for the optimization of temperature stability or linearity.
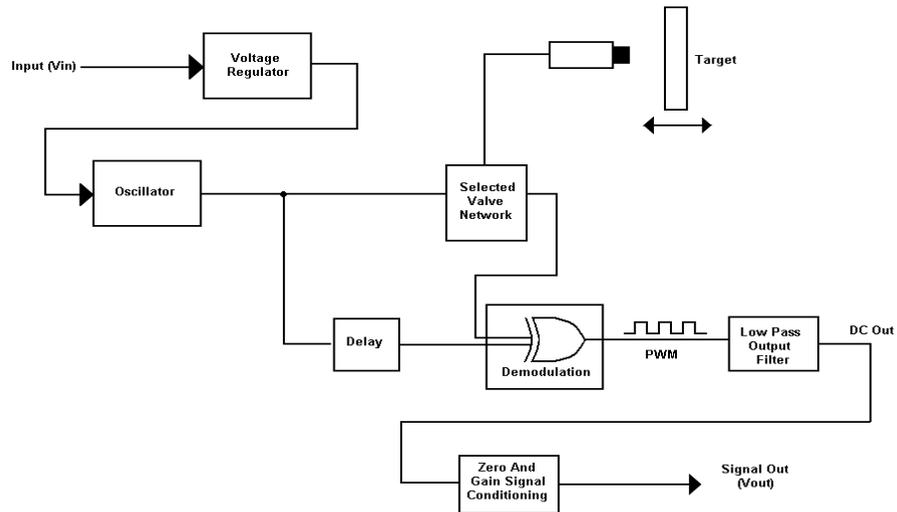
Applications

Applications span many areas, including new product research and design, manufacturing process control, and part fabrication and inspection, where the application requires high resolution.

Typical applications are:
    Stage positioning in Atomic Force Microscopy (AFM)
    Z-axis positioning in photolithography equipment
    Laser optics positioning
    Precision grinding
    Semiconductor wafer transport mechanisms
    High resolution spindle vibration
    OEM applications requiring cost effective high precision performance
    Laboratory research, development, and testing

Systems

The Kaman SMT-9700 series is a PWM based system. This system has a small footprint, is ideal for OEM configurations, has excellent resolution, and only requires a single ended power supply. Custom designs can be tailored to meet the customers needs, and 18 pin, SIP (Single In-line Package) cards are available for customers to integrate into existing motherboards.

Section 4 - Applying Inductive Measuring Systems

The acronym "**TERMS**" is a simple way to ensure that you have covered the fundamentals when applying an inductive measuring system. **TERMS** stand for **T**arget, **E**nvironment, **R**ange, **M**ounting, and **S**peed. This section addresses each of these fundamentals in detail.

4.1 Target

What type of material makes a good target? Since the inductive principle relies on an opposing current to be induced in the surface of the target material, it stands to reason that a good target should be highly conductive and have uniform electrical characteristics.

Material Properties

The resistivity and permeability of a target material affects the performance of an inductive system. Metallic targets with low resistive are the best materials for overall system stability (refer to Appendix C).

Magnetism

If the target material or classification is unknown, simply attempt to attach a hobby magnet to the material. If the magnet has a slight to strong attraction, the material is ferromagnetic, and if there is no attraction, the material is non-magnetic. Kaman uses 6061 T-6 Aluminum (non-magnetic) and 4130 Steel (ferromagnetic) as "default" materials for calibration, unless otherwise specified. Note: Ferromagnetic materials vary greatly; an evaluation by Kaman may be required when using a ferromagnetic material with sensors smaller than .5 inch diameter.

Thickness

Although the eddy current penetrates slightly into the target material, the current density is greatest at the surface. The current density decreases exponentially as it penetrates the material. The depth at which the current density is only 36% of the density at the surface is called one skin depth. Skin depth depends on the resistivity and permeability of the target and on the frequency of the system oscillator. Three skin depths are recommended for a suitable target (refer to Appendix C). A thinner target may be used in some applications, but performance is degraded and sensor performance may be affected by any conductive material behind the target.

Size and Shape

The size and shape of a target can have an effect on the system performance. The ideal target shape is a flat surface that is at least 2.5 to 3 times the diameter of an "unshielded" sensor, and 1.5 to 2 times the diameter of a "shielded" sensor. The target size must be

specified if it is smaller than recommended. When a system is used on a target smaller than it was calibrated with, the output sensitivity, effective range, resolution, linearity, and stability may be affected.   Successful calibrations have been performed on targets as small as ¼ of a sensor diameter.

1.5 to 2X Sensor Diameter

Shielded Sensor

2.5 to 3X Sensor Diameter

Unshield Sensor
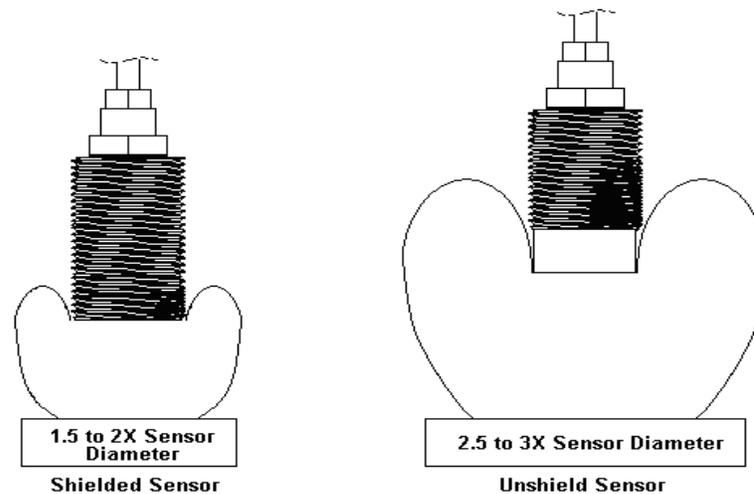
A general rule for cylindrical targets, such as a shaft, is to use a sensor that is 8 to 10 times smaller in diameter than the shaft diameter. This will make the shaft appear as an infinite plane. If the shaft is smaller than recommended, the system will be more sensitive to cross axis variation (errors caused by side to side movement of the target, which in turn creates non uniform eddy current coupling with the target).

8 to 10X Sensor Diameter

(Shielded or Unshielded)
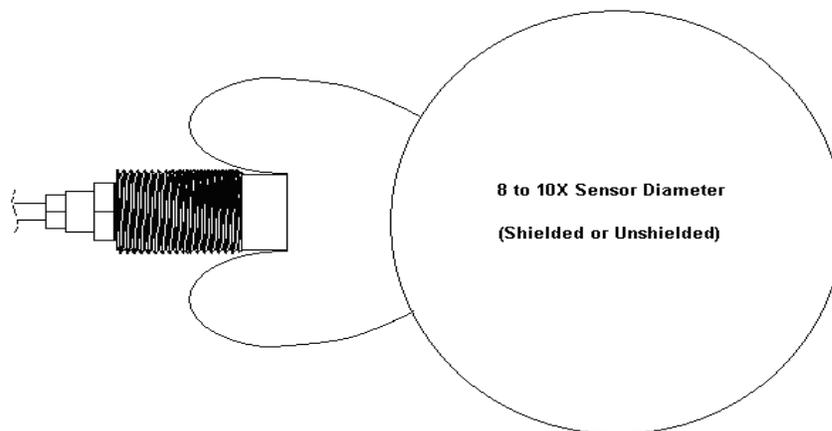
Surface

Since inductive technology has a large spot size, generally there is no difference between smooth and rough surfaces because the total area beneath the sensor is averaged. Impurities such as oil, grease, and dirt have negligible effects. Cracks in the target itself, if deep and wide enough, may appear as a discontinuity. Cracks less than two skin depths have a minimum effect (refer to Appendix C).

4.2 Environment

In general, inductive systems are well suited for all types of environments. Kaman offers sensors that operate when submerged in diesel fuel, oil, grease, antifreeze, brake fluids, machining oils, and even salt water. Kaman sensors are available that operate from cryogenic to 1100° F; however, special consideration must be given when operating over wide temperature ranges to insure optimum performance.

Temperature

Temperature changes are the most likely cause of measurement errors. However, resistance changes in the eddy current path are somewhat self-compensating. In nonmagnetic targets, the increasing resistivity with temperature of the conductor (target) is self-compensated by the increasing skin depth. Thus, the effective resistance of the current path remains constant. However, the target thickness must be sufficient to permit an increased skin depth penetration at higher temperatures (3 skin depths recommended). Ferromagnetic targets are less stable thermally due to the nonlinear behavior of permeability, which also varies skin depth.

Temperature variations at the sensor/target interface may cause thermal sensitivity shift, which affects gain and linearity. A factory temperature compensation option will minimize the effect on the thermal sensitivity shifts. Resetting the zero control corrects thermal zero shift. This occurs when temperature changes cause the resistivity in the sensor or cable to change. The zero control does not correct sensitivity shift.

Pressure

Pressure and vacuum do not affect performance of an inductive sensor. However, special consideration must be given to select a sensor that can survive and, if necessary, seal to the pressure boundary.

Vibration

As a general rule, standard Kaman sensors can withstand 100 G shock (1200 mSec, half sine wave) and 10 G peak vibration (20 Hz - 2 kHz sinusoidal), without significant performance degradation. Empirical studies have shown that system output is affected by

less the 1% of full scale output after being subjected to the above. The sensors used for testing were large diameter (>1.00 inch), hence, small, lower mass sensor could in theory withstand higher levels of vibration and shock without a significant degradation in performance.

Fluids

The medium between the transducer and the target is usually air at ambient pressure. However, any medium that is not too conductive at 1 MHz (such as water or oil) can be used. The system's output sensitivity can be adversely affected by slightly conductive fluids (e.g. salt water). Inductive sensors have been successfully used in applications in which the entire sensor was submerged in seawater, brake fluid, automatic transmission fluid, antifreeze, diesel fuel, and machining oils. Sensor construction and materials must be considered for fluid resistance.

EMI (Electro-Magnetic Interference)

Inductive sensors are susceptible to interference from electro-magnetic fields present at the location of the sensor transducer. This susceptibly is due to the very nature of how an inductive sensor operates. "EMI" is defined as any electro-magnetic disturbance that interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics and electrical equipment. It appears as an undesirable signal superimposed on the analog output of the system. For an inductive sensor, EMI generally comes from two main sources; close proximity of sensors to each other, or electro-magnetic fields in the mounting environment.

EMI due to sensor-to-sensor proximity is addressed in the sensor mounting section of this handbook (refer to Appendix B).

Interference from electro-magnetic fields present in the environment may or may not be a problem depending on their frequency and strength. Inductive sensors are typically excited with 1 MHz or 500 KHz carrier signals. In general, interferences that are not within +/- 10% of the carrier are filtered out by the demodulator circuit in the electronics. The demodulator may not filter out very strong fields (such as near windings of an electric motor), regardless of the frequency. For signals close to the operating frequency of the sensor or strong fields, shielding around the sensor to mitigate the field is the only way to reduce interference.

If a sensor must operate in an electro-magnetic field, non-ferrous target materials are recommended. Ferrous targets can experience permeability changes due to the field which will also be a source of error.

4.3 Range

Measuring Range

The measuring range is directly proportional to sensor diameter. Generally, the magnetic field generated by the sensor coil can be detected at a distance of about 2 times the coil diameter from the face of the sensor. This field extends not only to the front, but also to the sides to some degree and in back of the coil. Its strength decreases exponentially with distance from the coil. The sensor range is typically 30-50% of the sensor coil diameter for all full size targets. In the case of highly conductive targets (Brass, Aluminum, Copper, and Silver) the range can be extended to 65% coil diameter with a reduction in linearity and overall system stability. At distances greater than this, field strength is weak and typically not usable for stable performance.

An example is a sensor with a 0.120 inch coil diameter has an effective measurement range of 0.040 inch and a sensor with a coil diameter of 3.00 inch has an effective measurement range of 1.20 inch.

Space constraints often dictate the sensor diameter and mounting configuration. Because measuring range is proportional to sensor size, it affects sensor selection. Larger sensors provide greater measuring range, but typically less absolute resolution than a smaller sensor. Using only a portion of a sensor's measuring range high accuracy-band calibration improves overall performance.

Offset

Offset is the distance between the sensor face and the beginning of the measuring range. Sensor/target should never go inside the offset. An offset is necessary to keep the sensor a non contact device, and to put the sensor inductive characteristics in a more linear portion of its range.

Refer to Calibration Terminology in Appendix A.

4.4 Mounting

The quality of any measurement depends on the mounting fixture. Unstable or non-repeatable fixturing will yield non-repeatable results.

Fixture

The amount of conductive material in or near the mounting fixture will impact system performance. A sensor is "side-loaded" when its field interacts with conductive material other than the target. Shielded sensors reduce this effect. For optimum performance, keep conductive material out of this field if possible (see below). In-situ calibrations are recommended for optimum performance if conductive material other than the target will be in the sensor's field.

For more information on Fixturing refer to Appendix B.

Non Parallelism

The target and sensor should be parallel to each other for ideal performance. However, some non parallelism can exist without inducing significant error. The error associated with non parallelism is called "Cosine Error," and results in increased nonlinearity. A non parallelism of up to 3 degrees will increase nonlinearity less than 0.5% of full scale. Non parallelism of 10 degrees will increase non linearity approximately 4% of full scale.

Sensor to Sensor Proximity

When two or more sensors are mounted in close proximity to each other such that their electromagnetic fields intermix, some interference may be noted. This interference is in the form of cross talk resulting in beat notes whose frequency will be the difference between the frequencies of the oscillator in each unit. Synchronization refers to using one oscillator unit to drive multiple electronics. The oscillator driver, or Master, is connected to other units whose oscillators have been disabled. These units are referred to as the Slave units.

4.5 Speed

Surface Velocity

Surface velocity error is caused by "eddy current drag" which can occur when the surface velocity of a target, typically a rotating shaft, exceeds the recommended ratio of system oscillator cycles per coil window. Extreme surface velocity produces an erroneous output that appears as an increase in displacement when there actually is no increase in displacement. Put another way, the output increases in proportion to the target speed the target appears to be moving away due to less eddy current coupling. To obtain less than 1% velocity error, the oscillator cycles/coil window ratio should be greater than 50 for absolute displacement and greater than 10 for events (e.g. tachometer applications).

Surface Velocity formula for shafts:

$$\frac{(\text{Sensor Coil } \phi \bullet \text{Ocillator Fequency (Hz))}}{\text{Shaft } \phi \bullet \text{Revolutions}\Big/_{\text{Sec}} \bullet \pi} > 50$$

If the above equation is satisfied, the system should provide less than 1% error due to surface velocity.

Event Detection

If the above equation is greater than 10, the system is not suitable in precision measurement but can be used in applications for detecting events only. An example is for use as a tachometer in an automotive turbocharger or rocket engine turbo pump.

4.6 "TERMS" - Summary

TARGET

Material Properties
- Material conductivity is important when considering eddy current technology
- Properties table available in Appendix C

Magnetism
- Material will fall into three different classifications: nonmagnetic, slightly magnetic, and ferromagnetic.
- A hobby magnet can be used as a simple way to determine magnetic classification

Thickness
- A thickness 3 "skin depths" is recommended to insure the target is not seen through
- The skin depth varies based on material and operational frequency (see Appendix C)

Size/Shape
- As a general rule, 2.5 to 3 times the diameter of the sensor is recommended for a unshielded sensor and 1.5 to 2 times for a shielded sensor looking at a flat target
- For cylindrical targets, 8 to 10 times the sensor diameter is recommended for all sensor types
- Smaller sized targets can be calibrated

Surface
- Due to large "spot size", use for flaw detection accommodated during the process is not recommended
- High finish is not necessary to carry out measurement
- Surface impurities will not affect measuring capabilities

ENVIROMENT

Temperature
- Unstable temperature is the most likely cause of measurement error
- Temperature error can be minimized if customer fixturing is kept thermally stable

Pressure
- Sensors can operate in a vacuum and high pressure environment
- For pressure applications, the sensor design should be evaluated

Vibration
- Kaman sensors can withstand 100 G shock and 10 G of vibration with little effect on the sensor
- The smaller the sensor the larger the shock and vibration it can withstand

Fluids
- As a general rule, sensor performance is not affected by most nonconductive fluids (i.e. water, saltwater, oil, grease, cooling fluids, and etc.)
- Material and sensor structure must be evaluated before exposure to fluid

EMI
- Electro-magnetic fields close to the operating frequency of the sensor can cause interference
- Strong fields near the sensor can cause interference.

RANGE

Measuring Range
- Precision measuring range is 30-50% of the sensor coil diameter
- Target can be detected at distances up to 2 times the diameter of the sensor

Offset
- Target and sensor should never be closer to each other than specified offset
- Standard offset is optimized for the best performance

MOUNTING

Fixture
- Unstable or non-repeatable fixturing will yield non-repeatable results
- "Side loading" will affect sensor performance if not originally calibrated for

Non parallelism
- "Cosine error" results in an increase in non linearity
- At 3 degrees, the non linearity is less than .5% of full scale, but at 10 degrees nonlinearity increases to 4% of full scale

Sensor to Sensor Proximity
- If sensors are too close, the fields will interact with one another, producing cross talk
- Synchronization will eliminate cross talk

SPEED

Surface Velocity
- If target velocity exceeds the recommended ratio (see equation on page 14), then "eddy current drag" can affect the output
- At excessive velocity, the output will show the target as farther away

Event Detection
- For high speed applications, a high precision measurement may not be possible, but an inductive sensor can be used to detect events
- Tachometers and counters are examples of inductive sensors being used in high speed applications

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Section 5 - Performance

The performance of a system encompasses several different parameters, including; Output/Sensitivity, Resolution, Frequency Response, Non Linearity, Stability, and Accuracy. This section addresses each of these in detail.

5.1 Output/Sensitivity

A target movement towards or away from the sensor will cause the output to decrease or increase accordingly. The voltage or current can be adjusted to achieve the desired sensitivity of the system. Typical values for the output are 0 to 10 Vdc and 4 to 20 mA. It is beneficial in some cases to adjust the output voltage into Engineering Units which will allow easy determination of position. For instance, a calibrated range of .250 inches with a 0 to 2.500 Vdc output results in a sensitivity of 10 mV/mil.

5.2 Resolution

Typical resolution is 1 part in 10,000 (0.01%) with 1 part in 100,000 (0.001%) possible by giving up performance in other parameters. To increase the system resolution, it may be required to decrease the measuring range. It would be wise to evaluate what is actually required of the measurement so as to determine if range can be sacrificed for a smaller absolute value of resolution. Another option is to give up linearity for resolution and post process the data to correct for the poor linearity.

5.3 Frequency Response

The frequency response requirements are application specific. Static target measurements can have very high resolutions. As the target begins to move, as in a vibration measurement, the ability of the electronic circuit begins to lag that movement. As the target movement increases in speed with constant amplitude, the change in direction of the target causes the system output at the end of the movement to roll off. Ever increasing speed of movement increases the amount of roll off. The decrease in indicated displacement with increasing target speed drops off gradually to a point where the slope of the output curve takes a sharp drop. This point of transition is referred to in performance specifications as 3dB point. It is important to determine the speed of the target and compare it to the frequency response of the potential system to be employed to ensure there is enough frequency response to collect meaningful data about the movement.

5.4 Non Linearity

This is basically an error, or deviation from the theoretical straight-line output signal from the offset position to the maximum calibrated position. In applications that evaluate a movement for a force applied, a highly linear system may be desirable. In applications where the desire is to repeat a given position, linearity can be a rather insignificant specification. (Non-linearity is typically expressed in least squares deviation from a best fit line).

5.5 Stability

The stability of a system can be impacted by several factors, two of which are temperature and electronics.

Thermal Stability

Temperature impacts the stability of a system in two ways: Thermal Zero Shift and Thermal Sensitivity shift. Thermal Zero Shift is an offset shift and therefore affects all points in measuring range equally. Thermal Sensitivity Shift is a shift in the slope of the output. It takes place primarily in the upper 50% of the measuring range and becomes worse as the range increases.

Of these two thermal errors, Thermal Sensitivity Shift is of most concern since it affects the system output to displacement relationship. Other than controlling the measuring environment temperature, Thermal Sensitivity Shift can be minimized by either opting for factory temperature compensation over the temperature range of the measurement or by only utilizing the first 50% of the sensor range.

Long Term Stability

Long Term Stability, as the name implies, is related to time and commonly referred to as drift. Long Term Stability is uni-polar and is typically specified as a percent of Full Scale over a period of time such as 0.1%FSO/mo. Typically, this drift is an offset error caused by components within the electronics; it can be sensitivity error, which affects the slope of the output if it is being caused by sensor cabling.

Although Long Term Stability is inherent in the electronics, there are external influences such as fixturing which can have an impact. Therefore, the first step in resolving drift problems is to eliminate the external influences. Where Long Term Stability is a concern for the measurement, components such as potentiometers can be replaced with fixed resistors in some circuits.

5.6 Accuracy

The accuracy of a measurement system refers to its ability to indicate a true value exactly. Accuracy is related to absolute error. Absolute error ($\in$) is defined as the difference between the true value applied to a measurement system and the indicated value of the system:

$$\in = \text{True Value} - \text{Indicated Value}$$

from which the relative accuracy is found from

$$A = 1 - \left(\frac{\in}{\text{True Value}} \right)$$

Based on this definition, accuracy can be determined only when the true value is known, such as during a calibration.

An inductive system's accuracy can be adversely affected by several parameters (error source), including: temperature, nonlinearity, target frequency, and fixturing. Kaman does not provide system accuracy specifications since all of the parameters cannot be replicated for each specific application in the calibration laboratory.

APPENDICES

Appendix A Calibration Terminology

There are 3 basic calibrations: Single-Ended, Bipolar, and Differential. The following information and illustrations provide a description of the calibration, the definitions of the terminology used to specify the calibration parameters, and an example of the calibration specification.

Single-Ended Calibration

A single-ended calibration produces an output voltage that varies proportionally from 0 Vdc, when the target is at the position closest to the sensor, to some maximum positive voltage, when the target is at the position farthest from the sensor. The terminology used to define this type calibration is as follows:

        Offset: The closest the target will come to the sensor
        Measuring Range: The calibrated span beyond the offset
   Output: The span of the voltage related to the Measuring Range

Example of Single-Ended Calibration Specification:

        Offset: .015”
        Measuring Range: .120”
        Output: 0 to 1.200 Vdc

Single-Ended Calibration
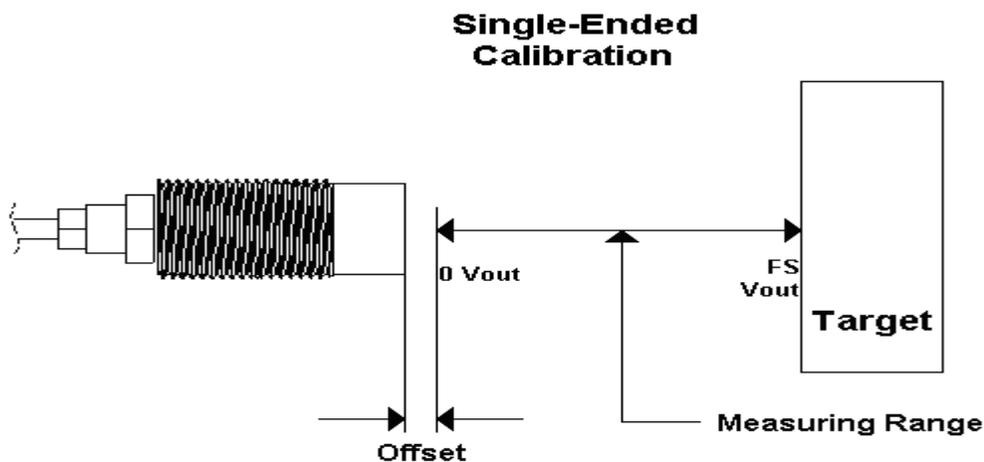
Bipolar Calibration

The Bipolar Calibration produces an output voltage that varies proportionally from a negative voltage for the first part of the measuring range to a positive output for the second part of the range. This calibration method is best suited for applications that require positive and negative system output from some nominal position. The terminology used to define this type calibration is as follows:

 Offset: The closest the target will come to the sensor
 Measuring Range: The calibrated span, expressed as +/-, beyond the offset
 Output: The span of the voltage, expressed as +/-, related to the Measuring Range

Example of Bipolar Calibration Specification:

 Offset: .015"
 Measuring Range: +/- .060"
 Output: +/- .600 Vdc

Bipolar Calibration
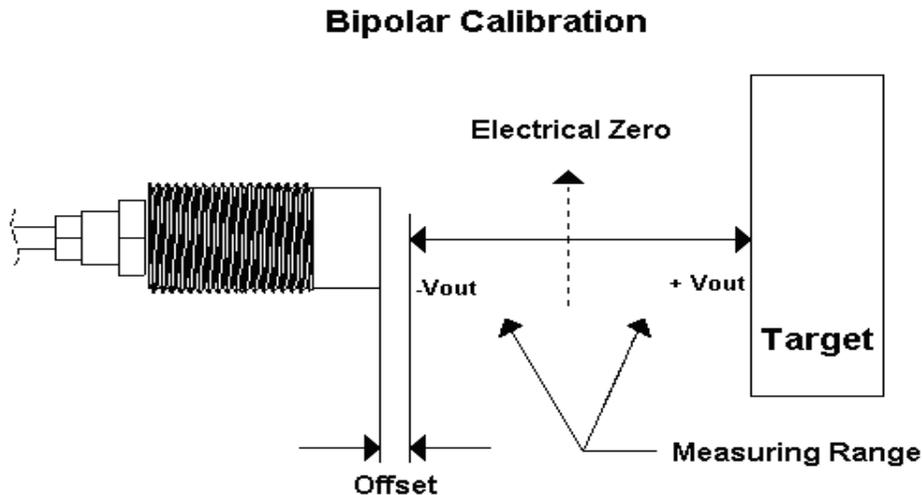
Differential Calibration

The Differential Calibration can be described as being similar to the Bipolar calibration, except that the term Offset is replaced with Null. In a Differential calibration, two sensors are used and the Null position is where both sensors are equidistant from the target. The output will be 0 Vdc at the Null position. The terminology used to define this type calibration is as follows:

> Null: The distance between the sensor face and the target at which the output is 0 Vdc
> Measuring Range: The calibrated span expressed in +/- units, referenced to the Null
> Output: The span of the voltage, expressed as +/-, related to the Measuring Range

Example of Differential Calibration Specification:

> Null: .075"
> Measuring Range: +/- .060"
> Output: +/- .600 Vdc

Differential Calibration
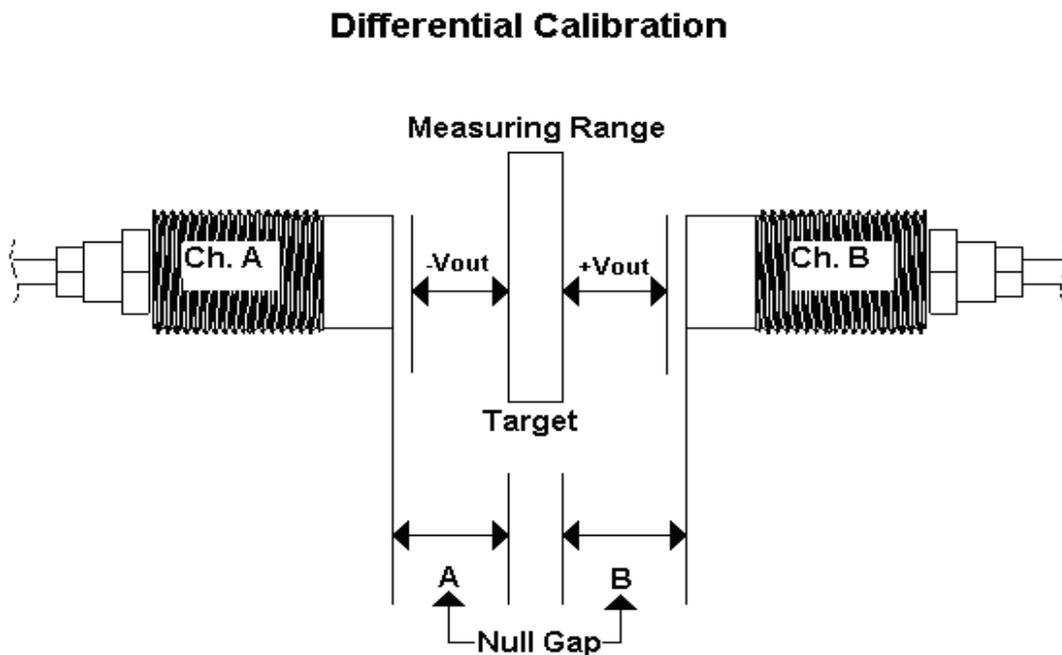
Appendix B Sensor Mounting Guidelines

The electromagnetic field (field) emitted by the sensor is omni-directional. Its size and shape is a function of the coil design, the shielding, and the application mounting configuration.

Conductive material other than the target entering into the field causes "side-loading". The most common form of side-loading comes from the counting configuration. Side-loading of the field can reduce the range of a sensor by as much as 50%. If the loading extends beyond the face of the sensor, the impact will be even greater.

Sensors may be classified as either shielded or unshielded. A shielded sensor is designed with a metal housing extending to the face of the sensor. An unshielded sensor is designed so that the metal housing stops some distance behind the face of the sensor. The illustration below shows the effects of the sensor housing shielding on the size and shape of the field.

Sensor Viewing Area

Shielded Sensor
1.5 to 2X Diameter

Unshielded Sensor
2.5 to 3X Diameter
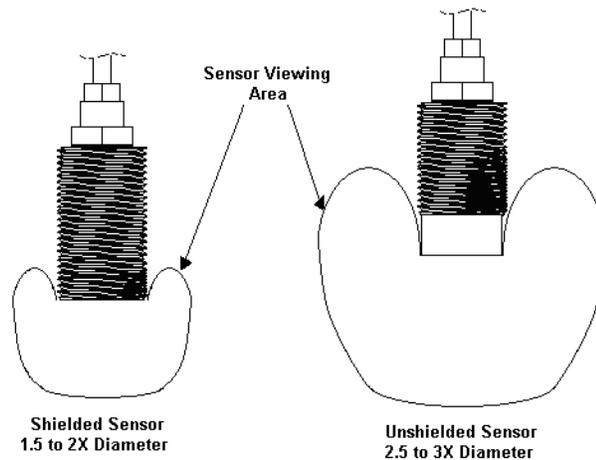
Shielded Sensors

The field of a shielded sensor is pre-loaded by the metallic sensor housing. The impact of loading by the mounting configuration is less with a shielded sensor due to this pre-loading. The illustration below provides guidelines for mounting shielded sensors.

Shielded Sensor
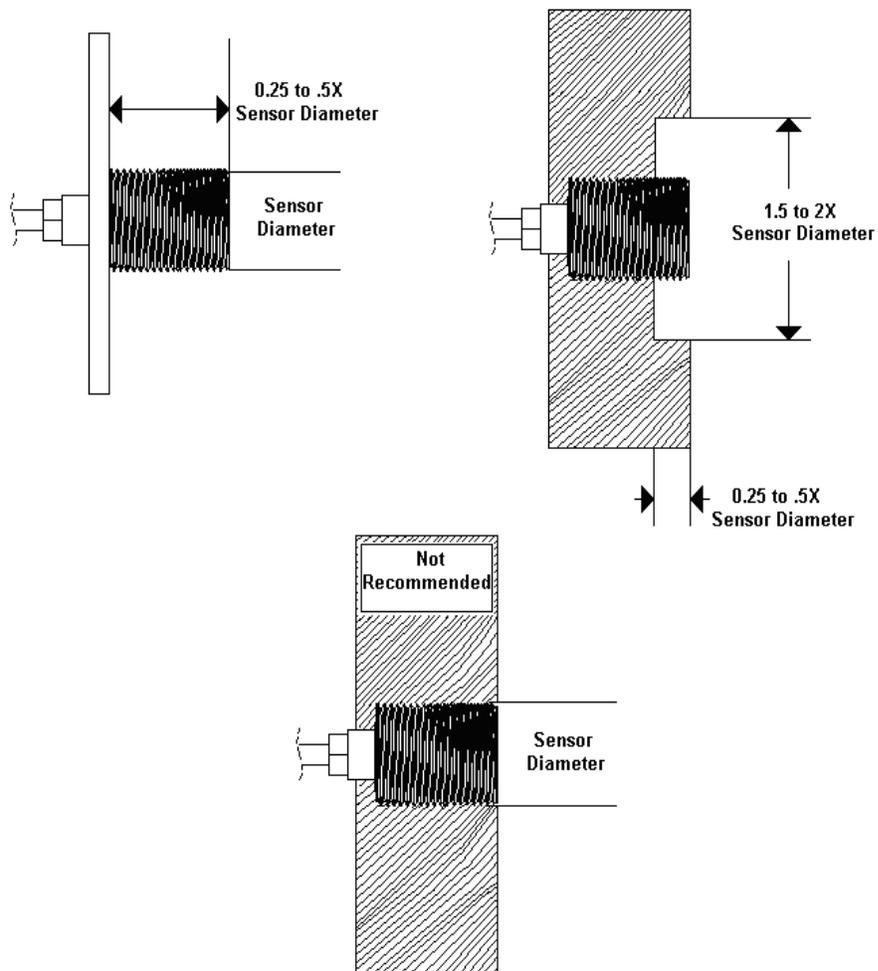
Unshielded Sensors

Since the metallic housing on an unshielded sensor stops some distance behind the sensor face, there is virtually no pre-loading of the field. As seen in the first illustration in this section, the field of the unshielded sensor is larger than that of a shielded sensor with the same diameter coil. Because the field is larger and not pre-loaded, an unshielded sensor is more susceptible to side-loading than a shielded sensor. The illustration below provides guidelines for mounting unshielded sensors.

Unshielded Sensor
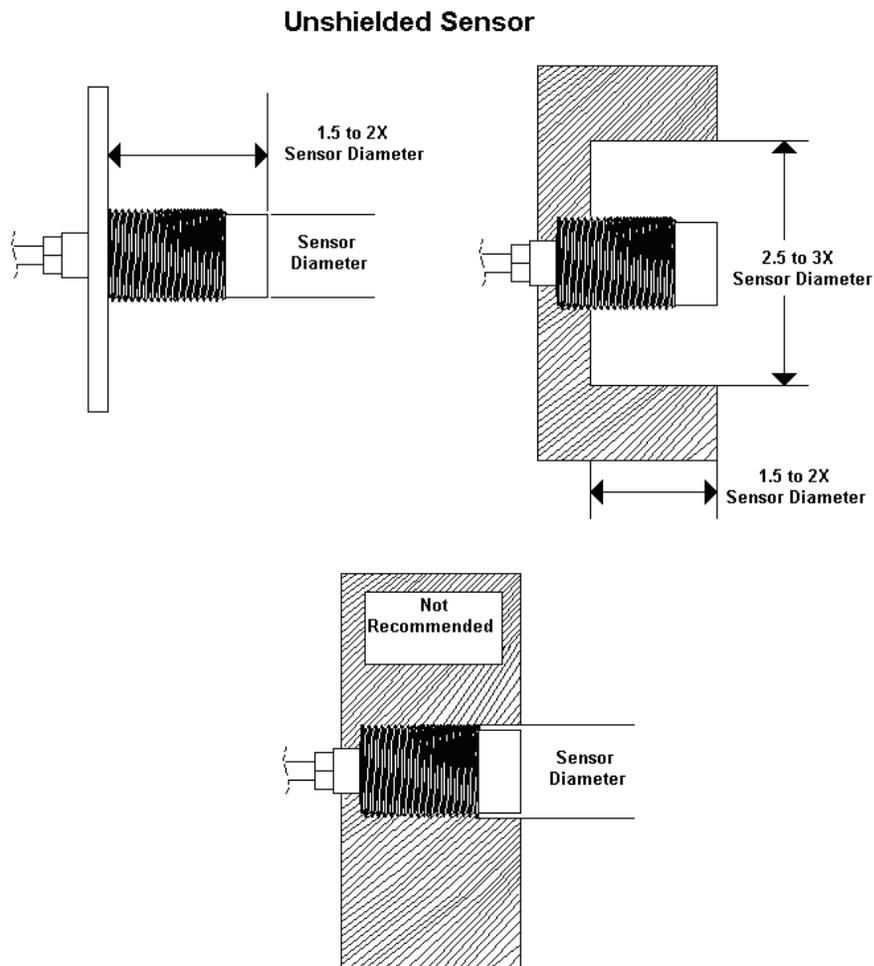
Appendix C Typical Target Material Characteristics

Material	Elect. Resistivity ρ (microhm-cm) @ 68F	Relative Magnetic Permeability μ	Classification	3 Skin Depths at 1 MHz (mil) recommended	3 Skin Depths at 500 kHz (mil) recommended
Aluminum & its alloys	4.5	1.00	nonmagnetic	13	18
Beryllium	4.3	1.00	nonmagnetic	12	17
Brass	7.4	1.00	nonmagnetic	16	23
Bronze	9.8	1.00	nonmagnetic	19	26
Cadmium	7.54	1.00	nonmagnetic	16	23
Copper	1.7	1.00	nonmagnetic	9	13
Gold	2.35	1.00	nonmagnetic	9	13
Graphite	1050	1.00	nonmagnetic	192	272
Inconel 625	127	1.00	nonmagnetic	67	95
Inconel 718	127	1.00	nonmagnetic	67	95
Inconel 725	127	1.00	nonmagnetic	67	95
Iridium	5.3	1.00	nonmagnetic	14	19
Lead	22	1.00	nonmagnetic	28	39
Magnesium	13.6	1.00	nonmagnetic	22	31
Palladium	10.8	1.00	nonmagnetic	20	28
Platinum	10.6	1.00	nonmagnetic	19	27
Silver	1.59	1.00	nonmagnetic	7	11
Tin (cast)	10.8	1.00	nonmagnetic	20	28
Titanium & its alloys	113	1.00	nonmagnetic	63	89
Tungsten	5.51	1.00	nonmagnetic	14	20
Uranium	37.5	1.00	nonmagnetic	36	51
Zinc alloys (cast)	6.5	1.00	nonmagnetic	15	21
SS 200 Series	69	1.02	slightly mag.	49	69
SS 300 Series	72	1.02	slightly mag.	50	71
17-4 PH SS	100	151	ferromagnetic	5	7
Carbon Steels	17.5	213.00	ferromagnetic	2	3
Chromium Steel	29	144.00	ferromagnetic	3	4
Cobalt	6.24	250.00	ferromagnetic	1	2
Cobalt Steel	28	56.00	ferromagnetic	4	6
Iron (cast)	65	5000.00	ferromagnetic	1	2
Molybdenum	5.17	100.00	ferromagnetic	1	2
Mumetal	60	20000.00	ferromagnetic	1	2
Nickel	7.85	600.00	ferromagnetic	1	2
SS 400 Series	60	850.00	ferromagnetic	2	3
Steel 1030	14	400.00	ferromagnetic	1	2
Steel 4130	65	450.00	ferromagnetic	1	2
Steel 416	60	400.00	ferromagnetic	2	3
Tungsten Steel	30	128.00	ferromagnetic	3	4

Glossary

A/D Converter | A device that converts an analog voltage to a digital representation.

Analog Output | Output voltage of a system that is a continuous function of the target position relative to the sensor.

Coupling Effect | Interaction between the electro-magnetic field generated by a sensor and the opposing electro-magnetic field generated by eddy currents in the target.

Cross Axis | Refers to movement perpendicular to the axis of measurement, such as a target moving across the fact of a sensor. Cross axis error is generated in the output by unexpected movement of either sensor or target which is perpendicular to the axis of the measurement.

Dimensional Standard | A standard of measurement or precision reference against which one correlates the output of the system, i.e., a micrometer fixture, feeler gauges, precision ceramic spacers, etc.

Drift | Undesirable change in system output over a period of time while the sensor / target position is constant. It may be unidirectional or cyclical and caused by such things as aging of the electrical circuits or environmental changes impacting the system.

Effective Resolution | An application dependent value determined by multiplying the equivalent input noise specification by the square root of the measurement bandwidth.

Equivalent RMS Input Noise | A figure of merit use to quantify the noise contributed by a system component. It incorporates into a single value factor influencing a noise specification, such as signal-to-noise ratio, noise floor, and system bandwidth. Given a measurement system's sensitivity and the level of "white noise", equivalent RMS input noise can be expressed in actual measurement units.

Full Scale Output (FSO) | The voltage output measured at full-scale displacement for which a system is calibrated. The algebraic difference between end points.

Gain	The function of increasing and decreasing sensitivity. Changing gain will increase or decrease the slope of the output curve.
Iteration	Repetition.
Linearity	The closeness of a calibration curve to a specified straight line.
Loading	The affect of conductive materials positioned within 3 times the diameter of a sensor that is a permanent part of the measuring environment.
Measurement Bandwidth	The difference between the upper and lower frequency response limits of a system
Noise	Any unwanted electrical disturbance or spurious signal that modifies transmitting display or recording of desired data.
Offset	The required gap between the sensor face and the target at zero range.
Output	The electrical quantity produced by the sensor and modified by the system as a function of target position relative to the sensor.
Pass Line	Refers to the target centered between two sensors. Typically it is referenced when making thickness measurements. A Pass Line error is generated in a thickness measurement when the target moves off center to a degree that the sensors no longer compensate for each others output errors.
Range	The spectrum of measured values that exists between the upper and lower limits of a sensor's measuring capability.
Repeatability	The ability of a system to consistently reproduce output readings when applying the same dimensional standard repeatedly under the same conditions and in the same directions.
Resolution	The smallest discernible change in target position relative to a reference.
Target	Object being measured by a sensor.

QUICK CONVERSION

1 Mil

Multiply by .001 – Inches

Multiply by 25.4 = Microns (µm)

Multiply by 0.0254 = Millimeters (mm)

1 Millimeter

Multiply by $1 \bullet 10^{-7}$ = Angstrom unit (A)

Multiply by 1000 = Microns (µm)

Multiply by 0.1 = Centimeters

Multiply by 0.03937 = Inches

Multiply by 0.001 = Meters

Multiply by 39.37 = Mils