KD-5100

Differential Measuring System
User's Manual

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ILLUSTRATIONS

KD-5100 SERIES
DIFFERENTIAL MEASURING SYSTEMS

SYSTEM SPECIFICATIONS:

Sensor Type   _____   Null Gap   _____

Offset   _____   Measuring Range   _____

Full Scale Output   _____   Scale Factor   _____

Target Material   _____

1.0 INTRODUCTION

This manual describes installation and use of the KD-5100, theory of operation, ways to optimize performance, special handling cautions, functional tests, and guidelines for fixturing and targets, and calibration procedures.

Calibration

Though there is a section on calibration, these systems are shipped from the factory calibrated for a user specified target, sensitivity, and measuring range. We calibrate these systems in a controlled environment using a precision laser as a primary dimensional standard. Since it is difficult for users to duplicate our calibration conditions, call us before attempting any adjustments of your KD-5100. On the other hand, it is equally difficult for Kaman to duplicate your actual application conditions, so special circumstances may dictate come calibration. Again, coordinate with a Kaman engineer first.

Maintainability

The KD-5100 is designed so that scheduled maintenance and adjustments are not required. The unit can be removed and replaced without special tools.

Environment

The KD-5100 provides specified performance after exposure to all natural and/or induced environments encountered during manufacture, test, transportation, handling, storage, installation, and removal operations.

2.0 THEORY OF OPERATION

The KD-5100 Differential Measuring System uses advanced inductive measurement technology to detect the aligned or centered position of a conductive target. Two matched sensors are positioned relative to the target so that as it moves away from one sensor it moves toward the other an equal amount.

The transducer operates on the principle of impedance variation caused by eddy currents induced in a conductive target located within range of each sensor. The coil in the sensor is energized with an AC current, causing a magnetic coupling between the sensor coil and the target. The strength of this coupling depends upon the gap between them and changes in gap cause an impedance variation in the coil.

In the KD-5100, the coils of a pair of sensors form the opposite legs of a balanced bridge circuit (Figure 1).
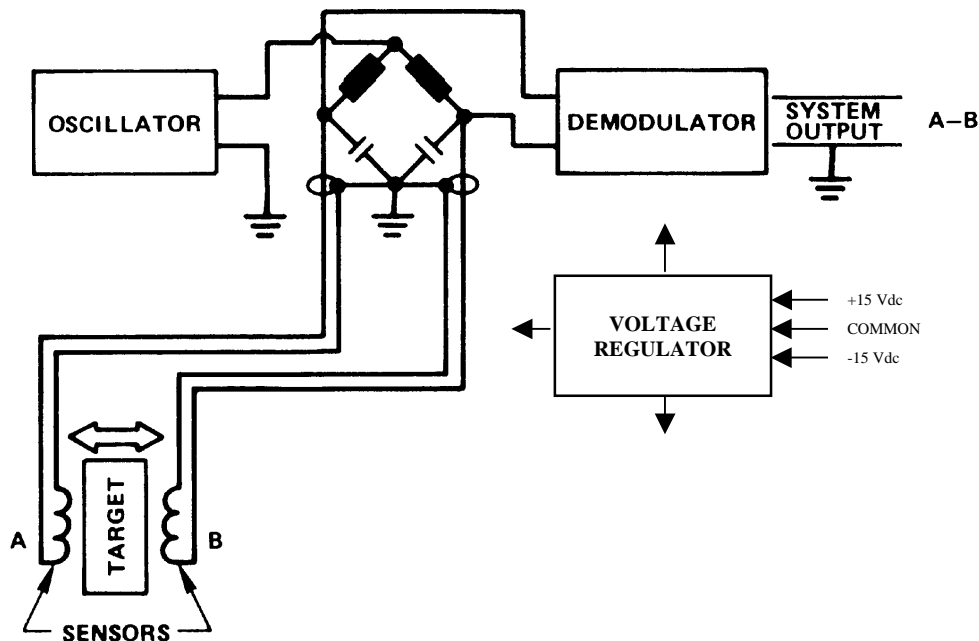
Figure 1 Block Diagram: Differential Measuring System

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 between the sensors. The bridge detects this imbalance and its output is amplified, demodulated, and presented as a linear analog signal directly proportional to the targets position. This is a bipolar signal that provides both magnitude and direction of misalignment. Only the differential output is available.

This differential configuration achieves its high resolution by eliminating the noise and drift any intervening summation and Log amplifiers normally add to the system.

Maximum performance depends upon advanced sensor technology. Factors critical to the high resolution of the KD-5100 are tighter manufacturing control, using significantly larger coils for a given range of operation, and electrically matching the sensors.

By using electrically matched sensors on opposing legs of the same bridge, temperature effects common to the sensors and cabling of a differential sensor pair tend to be cancelled. This is true for the mechanical aspects of the sensor/target system also. Assuming the thermal characteristics of each sensor track together, slight changes in sensor length due to temperature tend to be cancelled.

3.0 OPTIMUM PERFORMANCE

To optimize the performance of a KD-5100 system, a high (d) to (s) ratio is desired: (d) is the sensor coil diameter and (s) includes: the null gap, the positive measuring range, and ½ of the coil depth (Figure 2).

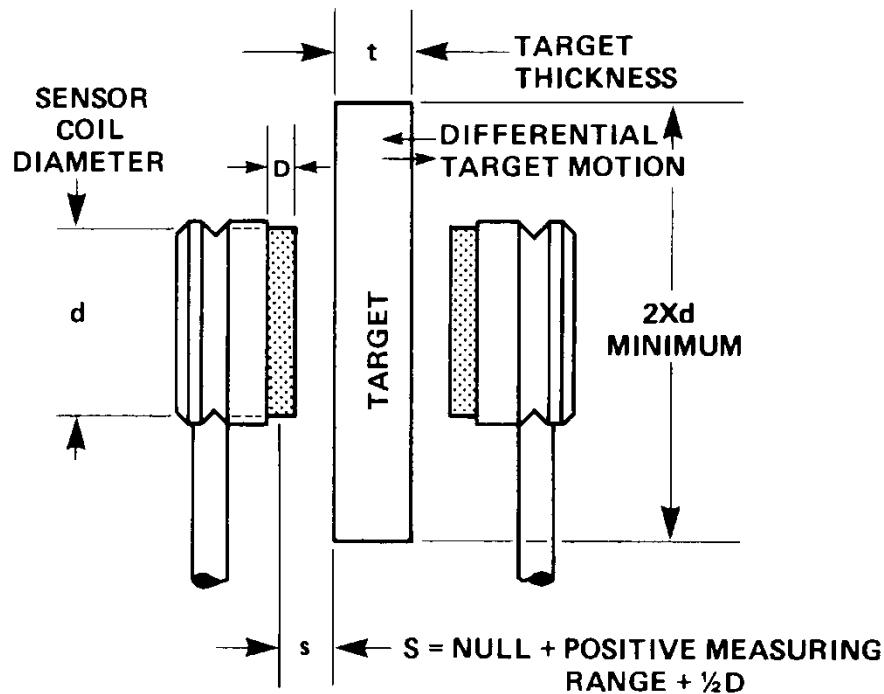
Figure 2 Sensor and Target Geometry

The 15N sensor used over the specified ±0.009" measuring range provides a d/s ratio of 3.08. The ratio for the 20N is 10.68. Therefore, if mounting space and target size permit, the 20N offers better performance over the specified measuring range.

For either sensor model, performance can be improved by decreasing the one variable, the measuring range. Significant reduction can provide a d/s ratio up to 35. This effectively lowers the noise floor and improves resolution, linearity, and thermal stability.

The temperature of the mounting surface and the environment for the electronics should not exceed the specified -20°C to 60°C (-4°F to $+140^{\circ}$F). For optimum performance, stabilize the temperature for the mounting surface/electronics at a constant temperature within this range, preferably 25°C.

4.0 APPLICATION INFORMATION

For differential measurement applications, the two electronically matched sensors are positioned on opposite sides or ends of the target (Figure 3). The sensor to target relationship is such that as the target moves away from one sensor, it moves toward the other an equal amount.
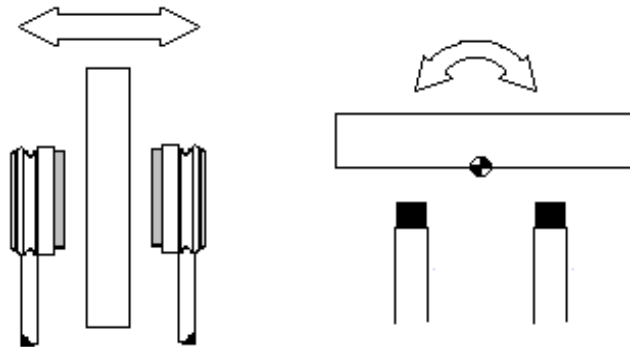
Figure 3 Differential Target Configurations

A standard system comes with two measurement axes (four sensors – two per axis) and can therefore be fixtured a number of ways to provide precise x-y alignment. Figure 4 illustrates target configuration for x-y alignment of an image stabilization mirror for an electro-optical application.

> **DO NOT MAKE ANY MODIFICATIONS TO CABLE LENGTH, SENSOR OR CALIBRATED TARGET MATERIALS WITHOUT CONSULTATING A KAMAN APPLICATION ENGINEER**
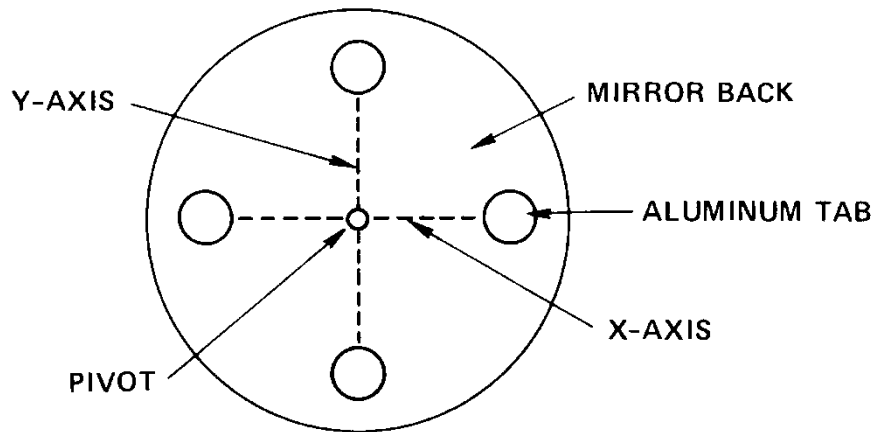
Figure 4 x-y Mirror Alignment Configuration

5.0 TARGETS

5.1 Material

Iron, nickel, and many of their alloys (magnetic targets) are not acceptable for use with the KD-5100.

Aluminum is preferred as the most practical target material. Aluminum targets can be mounted on materials with more stable temperature characteristics such as Invar or other substrates as long as target thickness guidelines are observed (Figure 5).
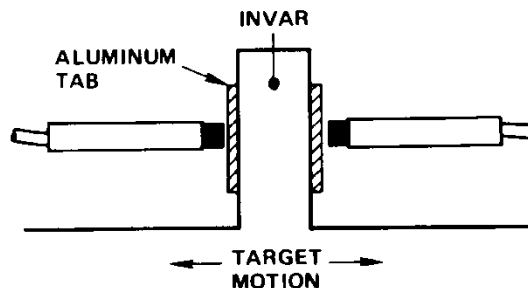
Figure 5 Aluminum Targets on Invar

These systems are set up to work with other nonmagnetic conductive targets on a special order basis. If you purchased a system for use with a target material other than aluminum, it has been calibrated (with selected component values) at the factory using that target material. An arbitrary change in target material may, at a minimum, require calibration or, not work at all.

5.2 Thickness

The RF field developed by the sensor is at a maximum on the target surface. There is penetration below the surface and the extent of penetration is a function of target resistivity and permeability. The RF field will penetrate aluminum to a depth of 0.022", a little more than three "skin depths" (at one skin depth the field density is only 36% of surface density and at two skin depths it is 13%). To avoid variations caused by temperature changes of the target, the minimum thickness should be at least three skin depths.

The depth of penetration depends on the actual target material used. In cases where the sensors are opposing each other, aluminum target thickness must be at least 0.050" to prevent sensor interaction.

Material	Thickness in mils
Silver and Copper	22
Gold and Aluminum	22
Beryllium	25
Magnesium, Brass, Bronze, Lead	58
300 Series Stainless	110
Inconel	110

Recommended minimum target thickness in mils.

5.3 Size

The minimum target size is at least 2 times sensor diameter.

6.0 SPECIAL HANDLING CAUTIONS

6.1 Sensors

Due to design requirements, the sensor coil is exposed. The sensors are shipped with protective caps. Keep them in place until installation of the sensors.

CAUTION: If any sharp object comes in contact with the coil face or edge and damages it in any way, this could short a number of turns in the coil, alter its impedance, and render the sensor useless.

6.2 Mounting Surface

The base plate of the electronics module has a smooth surface to enhance thermal conduction away from the electronics. Mounting the base plate flush with another surface will enhance thermal dissipation (assuming a mount surface with a temperature below 60°C). Base plate dimensions and mounting hole spacing are shown in Figure 6.
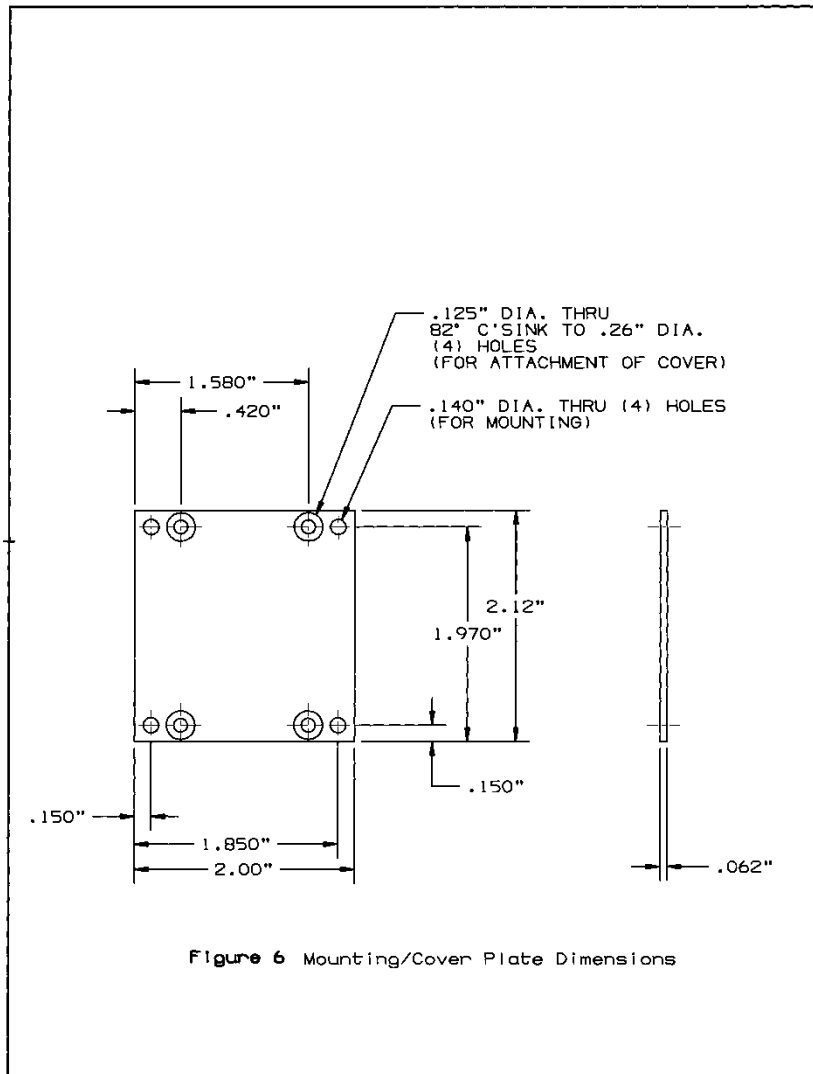
Figure 6 Mounting/Cover Plate Dimensions

7.0 FIXTURING

The user provides fixturing for the KD-5100 electronics and sensors. The following information establishes fixturing requirements for optimum system performance. The quality of the measurement is both a function of Kaman's system and your Fixturing.

Both the sensor and target fixturing must be structurally sound and repeatable.

7.1 Factors that degrade performance:

Unequal Loading: This refers to an unequal amount of conductive material within the field of one sensor of a pair as opposed to another (the sensor's field is approximately three times its diameter). Unequal loading causes asymmetrical output from the sensor, which induces non-linearity in the system output. Ideally, no conductive material other than the target should be in the sensor's field. Some loading may be acceptable if it is equal and the sensors are calibrated in place. Even then, sensor loading may cause non-linearity. If unable to calibrate – loading is too great.

Unequal Displacement: For targets using a pivot point mount (examples, Figures 3 & 4) the system should "see" equal displacement: i.e., the pivot point of the target is perfectly centered between the sensors. If the pivot point is a fraction of a mil off it can introduce non-linearity into the system.

7.2 Pivot point requirements:

The pivot point must be a common line between the centerline of a pair of sensors.

The axis of tilt must be a perpendicular bisector of a line between the centerlines of a sensor pair.

The pivot point must be positioned on the target so as not to introduce a translation error. This error, a function of angle, is caused by slight changes in the effective null gap as the target moves about the pivot. This results in non-linearity.

The pivot point must not change or move with time.
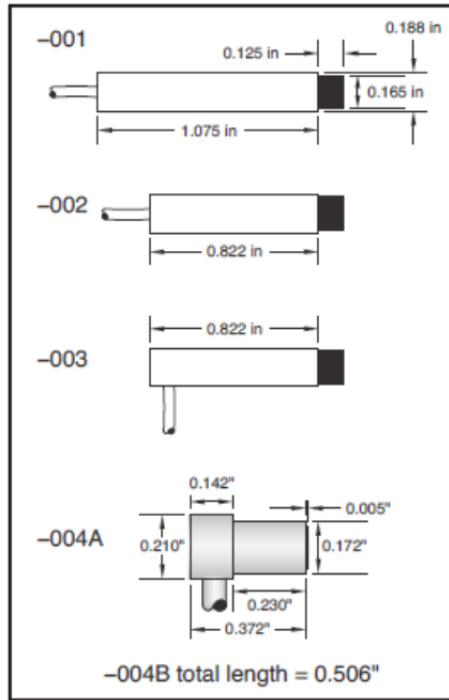
Figure 7 15N Sensor Dimensions
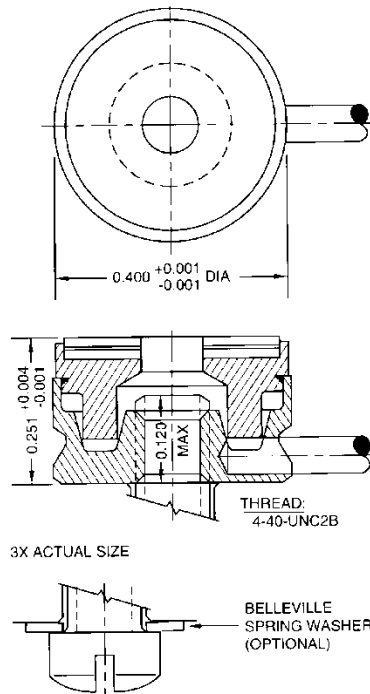
Figure 8   20N Sensor Dimensions

7.3 Sensor mounting considerations:

The sensors must be securely clamped. Sensor dimensions are shown in Figures 7 & 8.

The target must not strike the sensor face. The system has a null gap and a specified full measuring range. The difference between the null gap and measuring range is the offset distance for the sensors. This offset is necessary both to optimize performance and to keep the target from contacting and possibly damaging the coils in the sensor face.

The sensor coil is mounted at the face of both types of sensor. For purposes of mechanical nulling, measure distance from the sensor face. (For electrical nulling, the most accurate method, the null gap is referenced to the electrical centerline, which is one half of the coil depth – ½D, Figure 9.)

If the face of the sensor and the target surface are not parallel (if the sensor centerline is not perpendicular to the target) more than 2° to 3°, it will introduce error to the measurement.
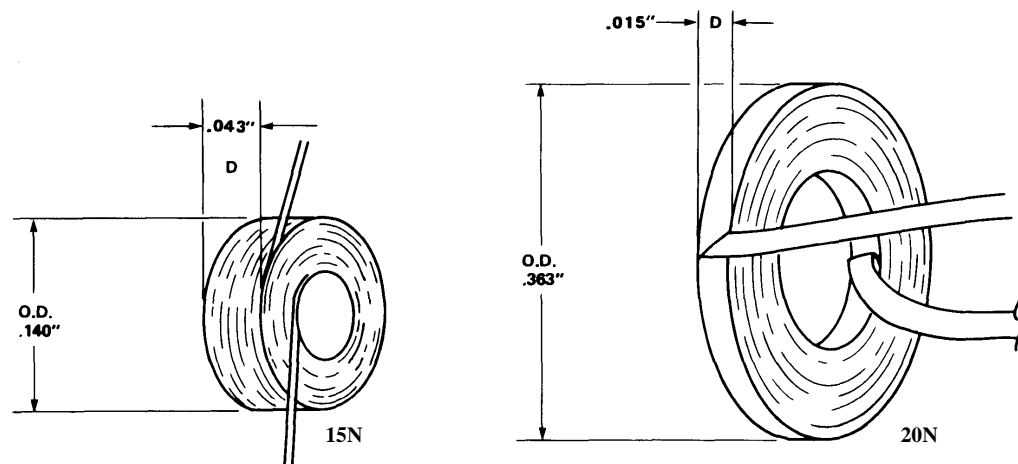
Figure 9 Sensor Coil Dimensions

8.0 CROSS-AXIS SENSITIVITY

Assuming you have stable and repeatable fixturing, and have followed all of the rules for target mounting, pivot points, etc., under certain conditions the system may exhibit signs of error we classify as cross-axis sensitivity.

8.1 Cross-axis sensitivity may occur under the following conditions:

The target must be one with x and y axes of tilt moving about a central pivot point (see Figure 4). When the target tilts full range in its x axis, it should be able to tilt full range in its y axis without any change in the indicated output of the x axis (or vice versa). This may not be the case. Cross-axis tilt can increase the coupling between the sensor and target, which causes a slight change in output, though there is no change in the actual distance between the sensor and target. This is a definition of error.

This error manifests itself as increased non-linearity of the output at the extreme end points of target travel only. (This non-linearity can change overall linearity from the specified 0.1% to about 0.3%.)

8.2 Additional points of emphasis about cross-axis sensitivity:

Again, the error manifests itself only at the end points of target travel (the last 20%) when the target tilts fully in both x and y axes.

The degree of error is related to the angle between the sensor and target face. As a general rule, for angles $\pm 1^{o}$ or less, there is virtually no problem with cross-axis sensitivity.

Sensor/target angle is a function of the distance between the sensor and target pivot, and the measuring range. A sensor with a range of ± 10 mils mounted 10 mils from the pivot will experience 45° of tilt at the end points. This is an extreme example but suffices to illustrate the point. A sensor with a ± 10 mil range must be mounted approximately 550 mils (13.9 mm – a little over ½ inch) from the pivot to achieve a 1° angle between sensor and target.

This phenomenon is related to basic physics and is stable, repeatable, small in magnitude, and can therefore be characterized. If necessary, users can provide a computer correction scheme.

Cross-axis sensitivity is not a problem for the majority of applications. If you anticipate or experience the problem, contact Kaman Precision Products for test data, which specifies under which conditions and to what degree cross-axis sensitivity exists.

9.0 PIN OUT and CONNECTOR ASSIGNMENTS

Sensor cable connections (Figure 10):

AXIS	CONNECTORS		SENSORS	
1	J3	J1	S3	S1
2	J4	J2	S4	S2
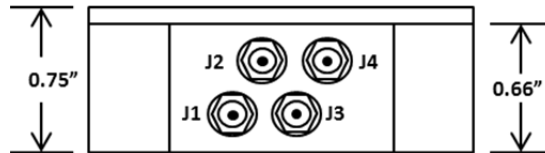
Figure 10 Sensor Cable Connections

Pin assignments for the Power/Signal line connector J5 (Figure 11):

PIN	FUNCTION
1	+15 VDC*
2	- 15 VDC*
3	Power Supply Common
4	Signal Output: Axis 1
5	Return Signal for Pin 4
6	Signal Output: Axis 2
7	Return Signal for Pin 6
8	Not Used
9	Not Used

Power Requirements	Tolerance
+15 VDC	+1.0, -0.5 VDC
-15 VDC	+0.5, -1.0 VDC

ITT Cannon Connector
MDM-9SL2P
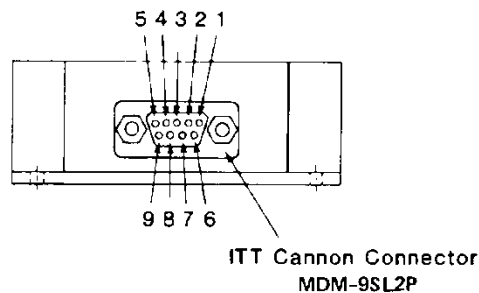
Figure 11 Power & Output Connections

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10.0 USER'S ABBREVIATED FUNCTIONAL TEST

This is not a calibration or installation procedure. This unit is factory calibrated, and installation guidelines are in the next section. This is simply a check to make sure the system is functioning upon receipt.

Perform this abbreviated functional test prior to installation of the electronics and sensors in the application fixture.

- Attach the power supply cable to connector J5 and apply power to the system.

- While monitoring the system output, place an aluminum target within 0.015" (15N sensor) or 0.020" (20N sensor) of sensor S3. It is preferable this step be accomplished using a fixture to hold the sensor and to control target movement. However, carefully hand holding and moving the sensor or the target will be sufficient for this check. (See Figure 11 for power and output connections at J5. The output for sensor S3 and S1 [axis 1] is at pin 4.)

- Slowly move the target through the sensor's measuring range to check for a full range of output for S3: 0 V to +10 V.

- Next: Check S1 for 0 V to –10 V.

- **Note:** This will not be a linear output and you may get an output with the sensor as much as 15 or 20 mils away from its target. That is OK since this check is only to confirm that the system is working.

- Repeat the above test for sensor S4 @ +10 V and S2 @ -10 V. Axis 2 output is pin 6.

If the output does not change during this test:

- Verify correct input voltage: +14.5 to 16 V and –14.5 to –16 V.

- Verify correct wiring to connector J5 (reference Figure 11).

- Verify sensor connection, and output connection to the correct channel for the sensor being checked:
    - S3 & S1 = axis 1 (pin 4),
    - S4 & S2 = axis 2 (pin 6).

- Still no change: contact Kaman Precision Products.

11.0 SENSOR INSTALLATION GUIDELINES AND PROCEDURE

11.1 Guidelines

The sensors should be positioned at the null gap using the Electrical Nulling Procedure. This installation procedure is the preferred method. Though both sensors may be positioned mechanically, this can cause a cumulative error. By electrically positioning the second sensor of a pair using system output, any existing error is self-canceling.

Install the sensors so that only the target interacts with the sensor's field. This means no conductive material other than the target within a circle around the sensor that is three times the sensor's diameter. The sensor field radiates in all directions. (Figure 12). Excessive back loading can also be a problem.

CAUTION: Be careful not to damage the sensor coil during this procedure
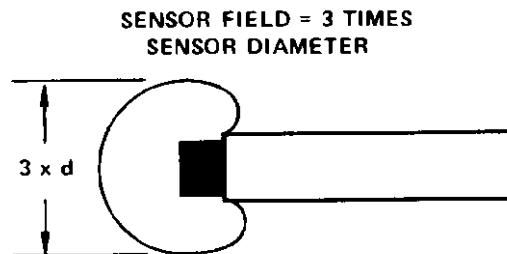
Figure 12 Sensor Field

11.2 Procedure

This procedure assumes the electronics are installed in the application fixture.

The sensor coil is mounted at the face of both sensors. For purposes of mechanical nulling, measure distance from the sensor face. For electrical nulling, the null gap is referenced to the electrical centerline, which is one half of the coil depth (½D, Figure 9).

11.2.1 Verify the target is in the null position.

11.2.2 Install the first sensor of a pair (start with S3) in the application fixture. Using a dimensional standard, precisely locate the sensor at the null gap specified at time of order. Secure the sensor and recheck its position.

11.2.3 Now install the second sensor of the pair (S1) in the fixture and position it to within a few mils of the required null gap. Connect the Power/Signal line to J5 and apply power to the system. Use the output from the system as a guide in the final positioning of this sensor (electrical nulling). Slowly move the second sensor toward or away from the target as necessary until the system output reads 0 VDC (ideally, 0.000 V). This output means the sensor is positioned correctly.

11.2.4 Repeat steps 11.2.1 through 11.2.3 for sensor S4 and S2.

11.2.5 The system is now ready for use.

12.0 CALIBRATION

KD-5100 systems are shipped from the factory pre-calibrated for a user specified measuring range, sensitivity, and target material. They do not normally require calibration or re-calibration. However, some applications may require the availability of this option.

The calibration procedure is very simple. However, it requires an accurate dimensional standard and a stable environment.

Some considerations……

Dimensional Standard: To calibrate, a dimensional standard (micrometer, laser interferometer, a weight to provide a known deflection, etc.) is required. This should be a standard known to be accurate and repeatable. Whether measuring in mils, microns, micro-radians, etc., a means of accurately positioning the target, using the dimensional standard, to the desired measurement units is required.

Kaman Precision Products uses a laser interferometer as a primary dimensional standard for calibration.

Recalibration: Recalibration to a sensitivity and/or measuring range significantly different from the factory calibration may not be possible. For example, if you purchased a standard system calibrated 0 to 9 volts over a 9 mil measuring range (1V/mil) and attempted to recalibrate for 9 volts over a 3 mil measuring range (3V/mil) there may not be sufficient gain adjustment to do this. These units are built with component values selected for each application. Therefore, changes in measuring range, sensitivity, or target material may not be possible and will require reconfiguration by Kaman Precision Products.

Thermal Equilibrium: The mounting/cover plate helps maintain thermal equilibrium inside the module and acts as a heat sink for the hybrid circuit. The hybrid has two watts of power to it and needs the cover plate for heat sinking. The calibration controls are located inside the unit and the cover plate must be removed to access them. Removing the cover plate removes its heat sinking function. Calibrating with the cover off and then reinstalling it will cause enough of a thermal gradient to throw the calibration off.

Kaman's solution is to use a cover plate with access holes for the calibration controls. This plate is available as an accessory from Kaman.

You may either obtain a calibration cover plate from Kaman or fabricate one from 0.062" thick aluminum. Dimensions and location of the holes are shown in Figure 13.
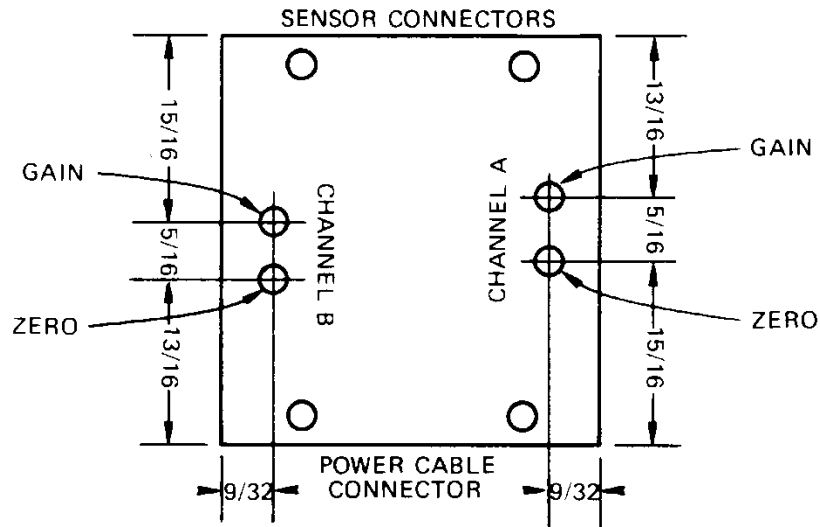
Figure 13 Calibration Cover Dimensions
(see Figure 6 for additional cover plate dimensions)

12.1 Equipment Required

- A dimensional standard
- A regulated ± 15 VDC power supply
- A voltmeter accurate to one millivolt or better
- An insulated adjusting tool ("tweaker") Kaman P/N 823977-T007
- A calibration cover plate

NOTE: When performing a system calibration, it is preferable to have the system installed in the application fixture at normal operating temperatures. This eliminates any shift in system output caused by moving the system from a calibration fixture to the application fixture (translation error).

12.2 Calibration Procedure Overview

Calibration involves the following steps:

- Null the Target
- Monitor the output of axis 1 - Adjust for 0.000 V output
- Move the target to full displacement – Adjust for full output voltage
- Return the target to the null position and check for an output of 0V±10mV
- Repeat for axis 2

The following information details these five steps.

12.3 Calibration Steps

12.3.1 Install the sensors in the application fixture (or calibration fixture) and accurately establish the null position for the target (see paragraph 11-3).

WARNING: Avoid eye contact with the silicone heat sink compound as it will cause temporary irritation.

12.3.2 Remove the four screws securing the cover plate and remove it. Silicone heat sink compound has been liberally spread between the hybrid case and the cover plate.

12.3.3 Install the calibration cover plate, power up the system and allow a 20 minute warm-up period. Monitor system output to verify stability.

NOTE: Output at null should be ideally 0.000 V. In practice, this is very difficult to achieve since it requires positioning the target to within micro-inches. Thermal expansion caused by simply placing a hand on the calibration fixture can cause more movement than a micro-inch. Get as close to 0.000 V as possible, not to exceed ± 10 mV.

12.3.4 To adjust for 0.000 V:

- Monitor the output of axis 1.

- Using the adjusting tool, adjust the zero control for axis 1 (Figure 14) for 0.000 V output.
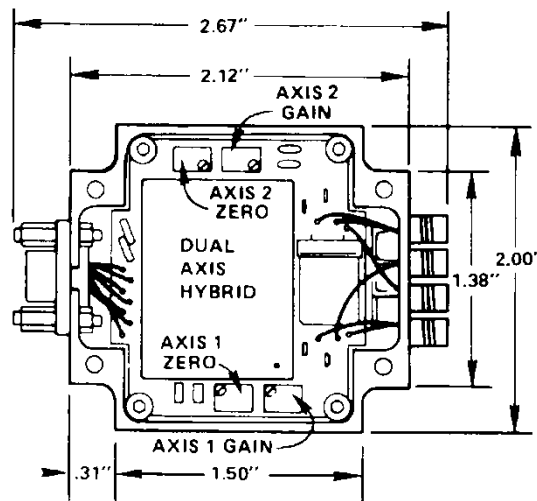
Figure 14 Zero & Gain Control Location Case Dimensions

12.3.5 Move the target through a known displacement to its maximum range and adjust the axis 1 gain control (Figure 14) for the desired output.

12.3.6 Return the target to the null position and check the output. You most likely will not see 0.000 V output unless you have a very good dimensional standard and very stable fixturing located in a controlled environment. When measuring at sub micro-inch levels, the world becomes rubber, and the fixturing may have expanded or contracted and you won't see 0.000 V again.

12.3.7 After returning the target to the null position, output should be 0.000 V (±10mV or less). If the output at null exceeds this, repeat the process. Calibration should not take more than two iterations.

12.3.8 Repeat the process for axis 2, monitoring the output at pin 6.

12.3.9 The system is ready for use.

13.0 TROUBLESHOOTING

What if the above calibration process doesn't work, if there is not enough gain for the desired output, or if a consistent 0.000 V ±10 mV cannot be achieved?

13.1 Insufficient Gain

When recalibrating for a sensitivity, measuring range, or target different from factory calibration specifications, there may be insufficient gain control.

Another cause for insufficient gain could be excessive loading of the sensors by conductive material (other than the target) within the field of the sensors. The sensor's field is approximately three times its diameter.

13.2 Can't Zero

The KD-5100 is an extremely stable measuring system - long term drift is less than 2 micro-inches per month. If the unit does not work, this would most likely be discovered during the Abbreviated Function Test, Section J. Our experience in numerous applications over years of use is that these systems either work or don't, and are not subject to "quirky" or "drifty" behavior. If unable to calibrate the system in no more than two iterations, the problem is most likely poor mechanical repeatability in the fixturing or actuating mechanisms.

 13.3 There is a way to check it out:

Do not make any adjustments to the calibration controls. Record how much time the next step takes.

Perform 12 to 15 iterations of moving the target from null to full range and back to null. Record the output at null each time. If successive readings of the output at null constantly very with no clear trend (drift) in one direction or the other, the problem is mechanical repeatability.

Now, stabilize the target at null and record the output. Leave the target at null for the same length of time it took to accomplish step two and monitor the output.

If the output remains constant, this confirms the problem was mechanical repeatability.

If the output drifts, the problem could be:
  - drift in the fixturing
  - drift in the target positioning servos
  - drift in the KD-5100

If you can positively eliminate all other variables as the source of the problem, contact Kaman Precision Products. Remember, if unable to calibrate the KD-5100 and it passed the Abbreviated Function Test, it is the least likely source of the problem.

14.0 TERMINOLOGY

Null Gap: The null gap is the point at which a target is equidistant from each sensor of a differential pair. The system output at null = 0 V. The actual gap is measured from the sensor face to the corresponding target face and includes a required offset (null gap = offset plus maximum measuring range).

Offset: The offset is the minimum distance between the sensor face and the target. Offset is necessary to prevent the target from striking the sensor face and to optimize performance (offset = null gap minus max range).

Measuring Range: The measuring range is the full range of target motion over which the various specifications such as resolution, linearity, and sensitivity can be met. The differential sensor arrangement yields a bipolar output and measuring range is expressed as a + and – value either side of the null position (measuring range = null gap minus the offset).
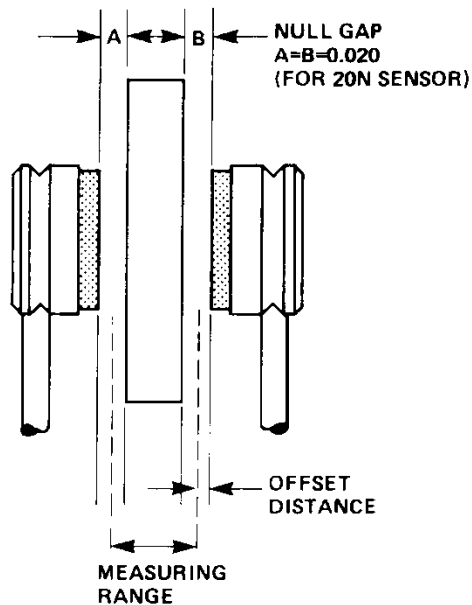
Figure 15 Null Gap, Offset, Measuring Range

Sensitivity: Sensitivity is the output voltage per unit of displacement. Usually expressed as millivolts per mil (0.001") or per millimeter.

Linearity: Linearity is the maximum deviation of any point of a calibrated system's output from a best-fit straight line. Express in actual units, e.g., micro-inches.

Equivalent RMS Input Noise: Equivalent RMS Input Noise is a figure of merit used to quantify the noise contributed by a system component. It incorporates into a single value, several factors that influence a noise specification such as signal-to-noise ratio, noise floor, and system bandwidth. Given a measuring systems sensitivity/scale factor and the level of "white" noise in the system, Equivalent RMS Input Noise can be expressed using actual measurement units.

Effective Resolution: Effective Resolution is an application dependent value determined by multiplying the Equivalent RMS Input Noise specification by the square root of the measurement bandwidth.

Example: An application with a 100Hz bandwidth using a KD-5100 with an Equivalent RMS Input Noise level of 0.2nm/ √Hz results in a system with an effective resolution of 0.2nm/ √Hz x √100Hz or 2 nano-meters.

15.0 CUSTOMER SERVICE INFORMATION

Should you have any questions regarding this product, please contact a Kaman Precision Products applications engineer at: 800-552-6267. You may also contact us through our web site at www.kamansensors.com, or general email address: measuring@kaman.com

In the event of a product malfunction, contact Kaman Precision Products for a return authorization.

APPENDIX A: Total System Specifications*(sensor, cable, and electronics)

PERFORMANCE (typical for stated measurement conditions)

	English (inches)	Metric (mm)
Null Gap		
KD-5100-15N	0.015±0.0001	0.381±0.003
KD-5100-20N	0.020±0.0001	0.508±0.003
Measuring Range		
KD-5100-15N	±0.009	±0.2286
KD-5100-20N	±0.009	±0.2286
Sensitivity or scale factor	1V/0.001±2%	40mV/0.001±2%
Non-Linearity		
KD-5100-15N	$\pm 2 \times 10^{-5}$	$\pm 0.5 \times 10^{-3}$
KD-5100-20N	$\pm 1 \times 20^{-5}$	$\pm 2.5 \times 10^{-4}$
Long Term Stability		
Stabilized at 70°F (21°C)	5×10^{-6}/month	1.27×10^{-4}/month
Thermal Sensitivity at Null		
(-20°F to 165°F)		
KD-5100-15N	$<5 \times 10^{-6}$/°F	$<2.3 \times 10^{-4}$/°C
KD-5100-20N	$<5 \times 10^{-6}$/°F	$<2.3 \times 10^{-4}$/°C
Frequency Response *	DC to 5 KHz	
Equivalent RMS Input Noise (DC to 5 KHz)	$4 \times 10^{-9}/\sqrt{\text{Hz max.}}$	$1 \times 10^{-7}/\sqrt{\text{Hz max.}}$
Effective Resolution	Equivalent RMS Input noise x $\sqrt{\text{bandwidth (Hz)}}$	

ELECTRICAL

Input Voltage	±15 VDC @ 70mA Typical
Power Consumption (system)	<2 Watts
Power Dissipation (15N sensors)	<10 microwatts per Sensor
(20N sensors)	<50 microwatts per Sensor
Output Characteristics	<5 ohms @ 5mA

TEMPERATURE

Electronics:	-4°F to 140°F (-20°C to 60°C)
Sensors:15N:	-62°F to 220°F (-55°C to 105°C)
20N:	-62°F to 220°oF (-55°C to 105°C)
20N (cryogenic):	4° Kelvin

WEIGHT (Electronics):   4 oz./113gr.

Performance is Typical for an aluminum target
* Bandwidth limited to 22 KHz ±5%

APPENDIX B: Measuring Range and Performance Tradeoffs

This Appendix presents the performance tradeoffs associated with range on the KD-5100 differential measurement system. In particular, the performance parameters that matter are non-linearity, temperature coefficient, and relative sensitivity (which affects resolution and electronics temperature coefficient).

This Appendix gives generalized results based on coil diameter and then applies the results to the two most popular sensors used with the KD-5100, the 15N and 20N.

Note: This Appendix illustrates typical performance and is not in itself a specification of performance. Actual specifications vary depending on a number of application variables and optimizations based on customer input. These illustrations do not account for those variables. Actual performance may vary from these estimates. Refer to the Kaman Specification sheet on the KD-5100 for specific details on actual performance.

Definitions

The following definitions are important when discussing performance.

Offset: The closest distance from the sensor face to the target that is still within the measuring range.

Null Gap: The distance from the sensor face to the target when the target is equidistant between the sensors. Reference figure 15.

Full Range (FR): The full range (sometimes referred to as Full Scale) of the system is defined as the total measurement distance. For example, a system with a ±10 mil (±0.25 mm) range would have a full range of 20 mils (0.5 mm). <u>All percentage measurements are percent of the full range.</u>

Coil Diameter: This refers to the diameter of the sensing coil itself. Eddy current systems performance at different ranges can most often be estimated generally (i.e. normalized) when considered as a percentage of the coil diameter. This allows the results to be applied broadly. The graphs following are based on this normalization. 'Full Range as a % of Coil Diameter' in the graphs means that for a coil diameter of 0.140" (~3.55 mm) the number of '50%' the full range would be about 0.070" (±35 mils) or ~1.77 mm (±0.885 mm) which is equivalent to ½ of the coil diameter.

Non-Linearity: Non-linearity is computed as the maximum error from a best fit (least squares) line and divided by the full range. A system with a non-linearity of ±0.2%FR and a ±10 mil (±0.25 mm) range (20 mil (0.5 mm) Full Range) would have a maximum deviation of 0.2%x20 mil=0.04mils (0.2%x0.5 mm=0.001 mm).

Estimated Non-Linearity of KD5100

Full Range as % of Coil Diameter

Best Fit Non-Linearity as % of Full Range
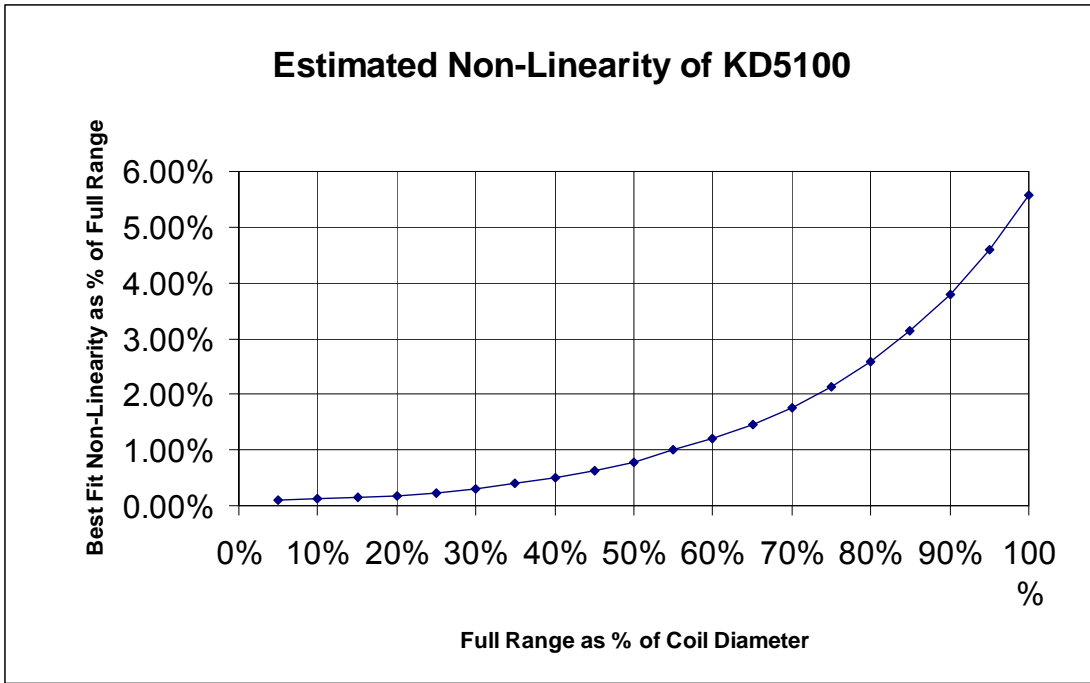
Below is the same graph on an expanded scale:

Estimated Non-Linearity of KD5100

Full Range as % of Coil Diameter

Best Fit Non-Linearity as % of Full Range
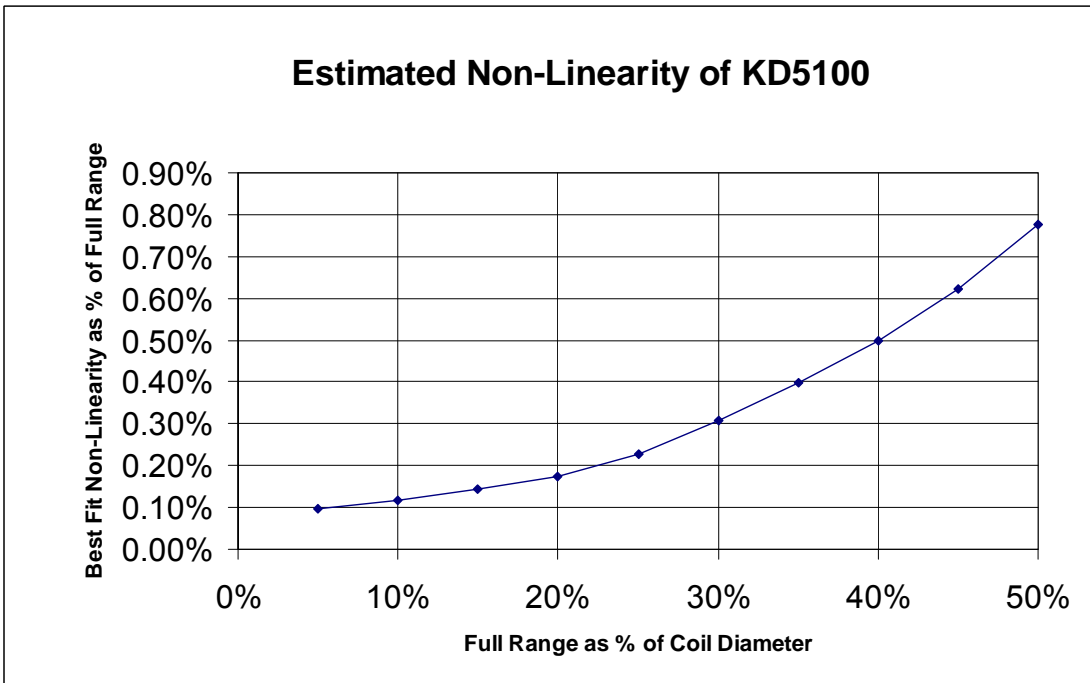
Temperature Coefficient: Temperature coefficient is calculated as the worst case shift over temperature. Temperature coefficient is also presented as a percentage of Full Range. A system with a full range of 20 mils (0.5 mm) would have system with a temperature coefficient of $\pm0.02\%FR/^{o}C$ or about 0.004 mils/^{o}C (0.1µm/^{o}C). Typically the temperature coefficient of a KD-5100 is the worst when at the extremes of the range and is excellent at the null position because the sensors are balanced. This appendix refers only to the temperature coefficient of the sensors and does not include the electronics temperature coefficient, which will be affected by the relative sensitivity.
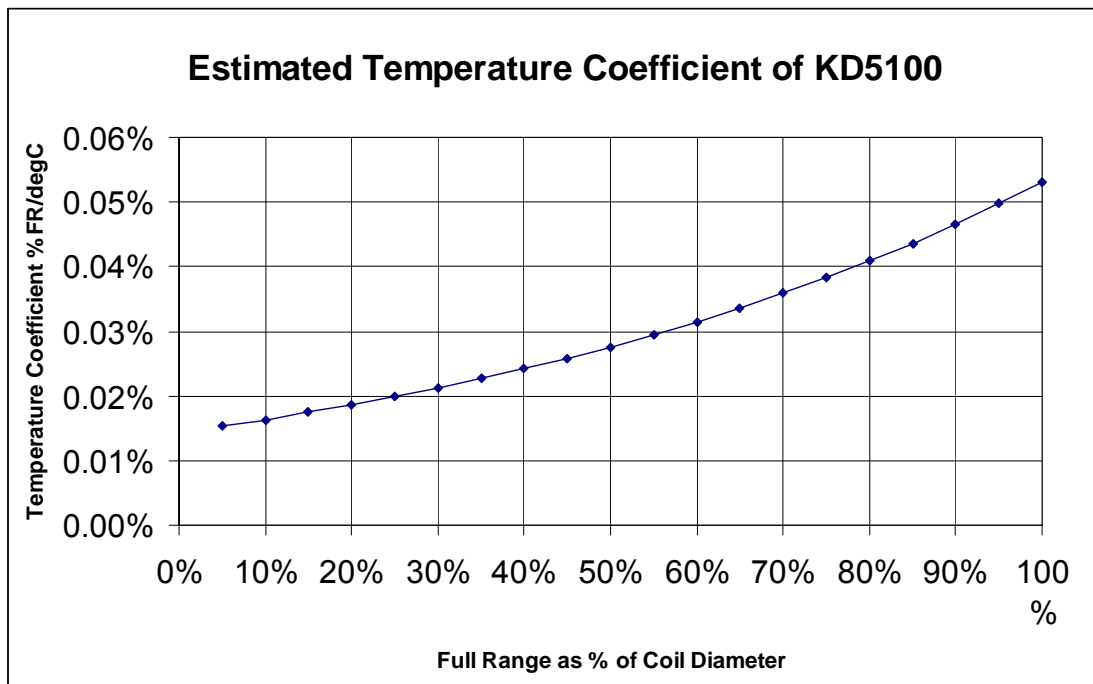
Relative Sensitivity: The relative sensitivity is a way of comparing the expected resolution of the system. The relative sensitivity is computed such that a system with a relative sensitivity of 1 would have resolution of 0.005%FR peak-to-peak when measured at a 1 kHz bandwidth with the sensors positioned at the extreme end of the measuring range. The resolution at null is generally better by a factor of 3. A relative sensitivity of 0.5 would effectively double the noise in the system and the temperature coefficient in the electronics as a percent of the measuring range (i.e. 1 is good, 0.5 is not as good).

This also affects the temperature coefficient of the electronics in the same relative manner. At a relative sensitivity of 1, the electronics has a temperature coefficient of approximately $\pm$ 0.01 to 0.02%FR/^{o}C (typically).

Estimated Relative Sensitivity of KD5100

Relative Sensitivity (y-axis, 0.00 to 1.20)
Full Range as % of Coil Diameter (x-axis, 0% to 100%)
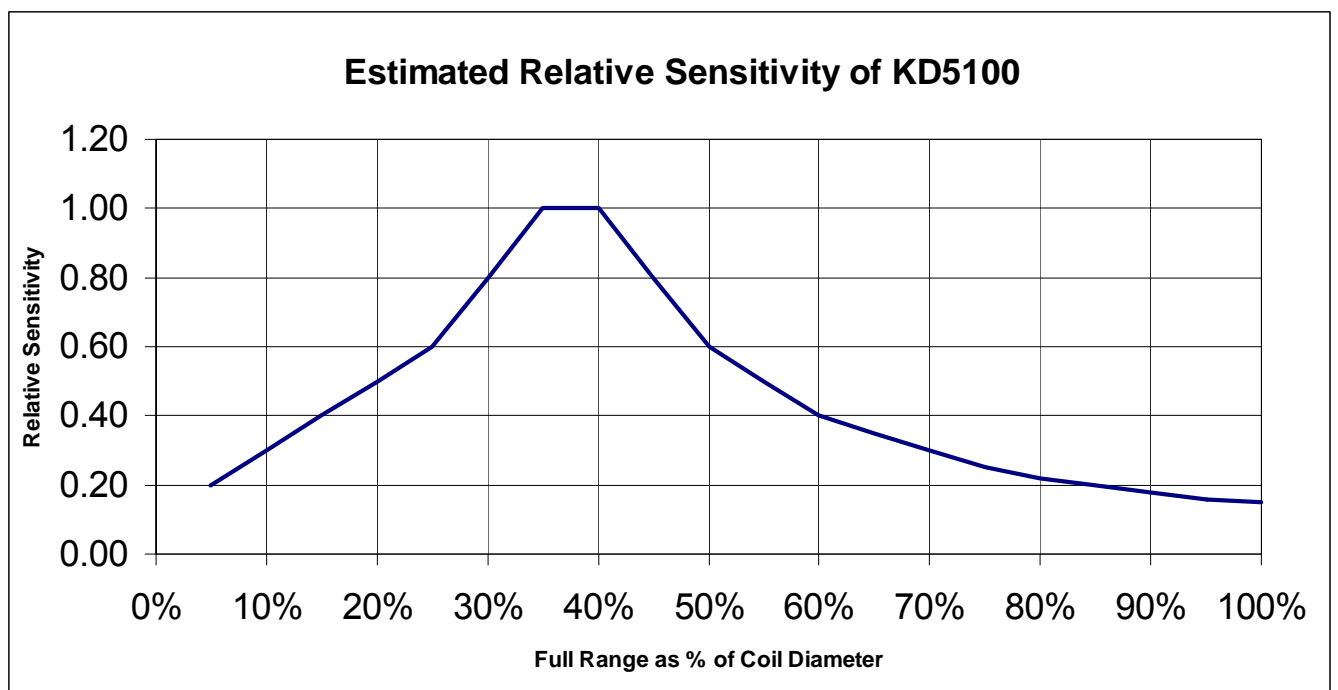
Relative Sensitivity is optimum around 35% of the measuring range for the following reasons:

At large ranges the output change remains constant while the range is increasing. This sensitivity number would obviously have a limit at '0' as the range increased to infinity.

At small ranges the output change is diminishing faster than the range is decreasing resulting in a net loss of sensitivity as a percentage of the measuring range.

Specific Example: 15N Sensors

The estimates below are for a 15N sensor. The estimates are based on the coil diameter of 143 mils (3.63 mm). The two tables contain the same data, just in different units. Note there is an entry for a 2 mil range (±1 mil) (~50 micron -- ±25 micron). This entry is based on a considerable amount of experience with this system and was not calculated.

KD-5100-15N Sensor -- English Units

%Coil Dia.	Offset, mil	Range, mil	Null, mil	Range (±) mil	NL, %FR	NL,mil	Sensor TC, %FR/°C	Sensor TC, mil/°C	Relative Sens.	FR Res, mil p-p @1kHz	Null Res, mil p-p @1kHz
1%	6	2	7	1	0.10%	0.002	0.05%	0.001	0.10	0.001	0.0003
7%	5	10	10	5	0.10%	0.010	0.02%	0.002	0.20	0.003	0.0008
14%	5	20	15	10	0.15%	0.030	0.02%	0.004	0.40	0.003	0.0008
21%	5	30	20	15	0.17%	0.052	0.02%	0.006	0.60	0.003	0.0008
28%	10	40	30	20	0.25%	0.100	0.03%	0.010	0.80	0.003	0.0008
35%	10	50	35	25	0.35%	0.175	0.03%	0.013	1.00	0.003	0.0008
49%	10	70	45	35	0.50%	0.350	0.03%	0.021	0.60	0.006	0.0019
56%	10	80	50	40	1.00%	0.800	0.03%	0.024	0.50	0.008	0.0027
63%	10	90	55	45	1.20%	1.080	0.04%	0.032	0.30	0.015	0.0050
70%	10	100	60	50	1.60%	1.600	0.04%	0.040	0.30	0.017	0.0056
77%	10	110	65	55	2.20%	2.420	0.04%	0.044	0.20	0.028	0.0092
84%	10	120	70	60	3.00%	3.600	0.05%	0.060	0.20	0.030	0.0100
91%	10	130	75	65	4.20%	5.460	0.05%	0.065	0.20	0.033	0.0108

KD-5100-15N Sensor -- Metric Units

%Coil Dia.	Offset, mm	Range, mm	Null, mm	Range (±) mm	NL, %FR	NL,µm	Sensor TC, %FR/°C	Sensor TC, µm/°C	Relative Sens.	FR Res, µm p-p @1kHz	Null Res, µm p-p @1kHz
1%	0.152	0.051	0.178	0.025	0.10%	0.05	0.05%	0.03	0.10	0.025	0.0085
7%	0.127	0.254	0.254	0.127	0.10%	0.25	0.02%	0.05	0.20	0.064	0.0212
14%	0.127	0.508	0.381	0.254	0.15%	0.76	0.02%	0.10	0.40	0.064	0.0212
21%	0.127	0.762	0.508	0.381	0.17%	1.33	0.02%	0.15	0.60	0.064	0.0212
28%	0.254	1.016	0.762	0.508	0.25%	2.54	0.03%	0.25	0.80	0.064	0.0212
35%	0.254	1.270	0.889	0.635	0.35%	4.45	0.03%	0.32	1.00	0.064	0.0212
49%	0.254	1.778	1.143	0.889	0.50%	8.89	0.03%	0.53	0.60	0.148	0.0494
56%	0.254	2.032	1.270	1.016	1.00%	20.32	0.03%	0.61	0.50	0.203	0.0677
63%	0.254	2.286	1.397	1.143	1.20%	27.43	0.04%	0.80	0.30	0.381	0.1270
70%	0.254	2.540	1.524	1.270	1.60%	40.64	0.04%	1.02	0.30	0.423	0.1411
77%	0.254	2.794	1.651	1.397	2.20%	61.47	0.04%	1.12	0.20	0.699	0.2328
84%	0.254	3.048	1.778	1.524	3.00%	91.44	0.05%	1.52	0.20	0.762	0.2540
91%	0.254	3.302	1.905	1.651	4.20%	138.68	0.05%	1.65	0.20	0.826	0.2752

Specific Example: 20N Sensors

The estimates below are for a 20N sensor. The estimates are based on the coil diameter of 363 mils (9.22 mm). The two tables contain the same data, just in different units.

KD-5100-20N Sensor -- English Units

%Coil Dia.	Offset, mil	Range, mil	Null, mil	Range (±) mil	NL, %FR	NL,mil	Sensor TC, %FR/ºC	Sensor TC, mil/ºC	Relative Sens.	FR Res , mil p-p @1kHz	Null Res, mil p-p @1kHz
3%	10	10	15	5	0.10%	0.010	0.02%	0.002	0.10	0.005	0.0017
6%	10	20	20	10	0.10%	0.020	0.02%	0.004	0.20	0.005	0.0017
8%	10	30	25	15	0.10%	0.030	0.02%	0.006	0.30	0.005	0.0017
11%	20	40	40	20	0.15%	0.060	0.02%	0.008	0.35	0.006	0.0019
14%	20	50	45	25	0.15%	0.075	0.02%	0.010	0.40	0.006	0.0021
19%	30	70	65	35	0.20%	0.140	0.02%	0.014	0.45	0.008	0.0026
22%	30	80	70	40	0.20%	0.160	0.02%	0.016	0.60	0.007	0.0022
28%	30	100	80	50	0.25%	0.250	0.03%	0.025	0.65	0.008	0.0026
41%	35	150	110	75	0.50%	0.750	0.03%	0.045	1.00	0.008	0.0025
55%	35	200	135	100	1.00%	2.000	0.03%	0.060	0.60	0.017	0.0056
69%	35	250	160	125	1.50%	3.750	0.04%	0.088	0.30	0.042	0.0139
83%	35	300	185	150	3.00%	9.000	0.05%	0.150	0.20	0.075	0.0250
96%	35	350	210	175	5.50%	19.250	0.06%	0.210	0.15	0.117	0.0389

KD-5100-20N Sensor -- Metric Units

%Coil Dia.	Offset, mm	Range, mm	Null, mm	Range (±) mm	NL, %FR	NL,µm	Sensor TC, %FR/ºC	Sensor TC, µm/ºC	Relative Sens.	FR Res , µm p-p @1kHz	Null Res, µm p-p @1kHz
3%	0.254	0.254	0.381	0.127	0.10%	0.25	0.02%	0.05	0.10	0.127	0.0423
6%	0.254	0.508	0.508	0.254	0.10%	0.51	0.02%	0.10	0.20	0.127	0.0423
8%	0.254	0.762	0.635	0.381	0.10%	0.76	0.02%	0.15	0.30	0.127	0.0423
11%	0.508	1.016	1.016	0.508	0.15%	1.52	0.02%	0.20	0.35	0.145	0.0484
14%	0.508	1.270	1.143	0.635	0.15%	1.91	0.02%	0.25	0.40	0.159	0.0529
19%	0.762	1.778	1.651	0.889	0.20%	3.56	0.02%	0.36	0.45	0.198	0.0659
22%	0.762	2.032	1.778	1.016	0.20%	4.06	0.02%	0.41	0.60	0.169	0.0564
28%	0.762	2.540	2.032	1.270	0.25%	6.35	0.03%	0.64	0.65	0.195	0.0651
41%	0.889	3.810	2.794	1.905	0.50%	19.05	0.03%	1.14	1.00	0.191	0.0635
55%	0.889	5.080	3.429	2.540	1.00%	50.80	0.03%	1.52	0.60	0.423	0.1411
69%	0.889	6.350	4.064	3.175	1.50%	95.25	0.04%	2.22	0.30	1.058	0.3528
83%	0.889	7.620	4.699	3.810	3.00%	228.60	0.05%	3.81	0.20	1.905	0.6350
96%	0.889	8.890	5.334	4.445	5.50%	488.95	0.06%	5.33	0.15	2.963	0.9878

Application Variables and Caveats

The following application variables will also affect performance. The effects listed are not considered in the results of the tables above and must be considered separately.

Sensor Loading: Sensor loading by conductive materials that are incidentally in "view" of the sensors can affect the results significantly and must be considered on a case-by-case basis. The discussions in this appendix assume that incidental materials do not load the sensor.

Cosine Error: This is error that occurs when the target movement is from tilting as in a fast steering mirror assembly and can become significant at larger measuring ranges.

Cross Axis Sensitivity Errors: This error occurs in 2 axis measurements of tip and tilt (common in fast steering mirrors) and can become significant at larger measuring ranges.

Setup Error: The system can become very sensitive to the null gap position when setup for very small ranges. Changes in the null gap will affect both the sensitivity and temperature coefficient. Usually only significant problem on ranges of <±10 mils (<±0.25 mm).

Target Effects: Eddy current sensors are significantly affected by the target material resistivity and permeability. Aluminum targets are considered in this appendix. In general the KD-5100 is best used with non-magnetic (relative permeability ≥ 1), low resistivity targets. The effect this has on the sensor is dependent on the operating frequency and coil diameter.

Cable Length: The KD-5100 sensors are passive. This means that the cable is an integral part of the sensor and affects measurement performance. The data presented assumes a 2 meter cable length. Actual results may vary with different cable lengths. Long cables are especially bad for performance because they degrade the effective Q of the sensor and increase the inherent temperature coefficient of the sensor coil. Long cables will also cause problems with thermal drift and variations in the output caused by cable movement.

Optimization: In the data presented, the circuit was optimized for each range. This means that the component values in the circuit may be different for each specific measuring range. The system will not get the performance shown simply by changing the range and recalibrating – it would require factory optimization. The system could also be optimize for a specific parameter (ex. temperature) and achieve better performance in that category – allowing the other performance parameters to be worse. The data shown for a specific range is a compromise of all the performance parameters. At each measurement range listed the linearity, temperature coefficient, and sensitivity listed are achievable simultaneously.

Method of Computing Performance

These results are based mainly on simulations. First the sensor inductance and resistance was computed using a modeling program. Then the effect of 2 meters of cable was factored in taking in consideration the transmission line effects of the cable. After that the resultant inductance and resistance was put in a model to simulate the circuit bridge network. The performance in each case was optimized to provide temperature coefficient as close to .02%FR as possible while adjusting the parameters for optimal linearity and reasonably good output. The resulting data was then fit to exponential curves to provide a continuous function of non-linearity and temperature coefficient vs. coil diameter (and the fit was very good). Finally, the results were then adjusted slightly based on data from actual systems and engineering judgment.

This means the system can be adjusted for better temperature coefficient if linearity and resolution are not a concern. Better resolution can be obtained at the expense of temperature coefficient. The tradeoffs were made to provide the best overall accuracy. What good is excellent resolution if the temperature coefficient causes the output to drift out of range?

In general, the results are reasonably accurate from about 10-50% of the coil diameter. Ranges of less than 10% will have additional errors not accounted for such as thermal expansion of the sensor body. Ranges less than 10% and greater than 50% will also have errors due to mismatch in the sensors and electronics.

A Note about Small Ranges

There is a point of diminishing returns when the range is small relative to the coil diameter. At a range of about 20% of the coil diameter, the amount of change in the measured variable becomes small rapidly. This causes the inherent output of the system to be reduced such that as more gain is added in the electronics to compensate, effective resolution does not increase. In fact, noise as a % of the range starts to increase. Significant errors can also occur from sensor body thermal expansion and component matching in the electronics. The 'break even' point is at a range of about 5% of the coil diameter. This means that reducing the range will not improve effective performance and dynamic range will be reduced. A range that is too small also makes it more difficult to set up the sensor within its measurement range.

Other Observations

1. Performance degrades rapidly when the range exceeds 50% of the coil diameter.
2. There is a limit (floor) to the resolution and accuracy when operating over very small ranges (< 5% of the coil diameter).
3. Optimum performance is obtained with a measuring range approximately 35% of the coil diameter. This is where the best tradeoff between resolution, non-linearity, and temperature coefficient will be achieved.

APPENDIX C: Output Filter Characteristics of the KD-5100

Applications utilizing the KD-5100 as the displacement feedback in closed loop systems generally require information about the gain and phase delay vs. frequency. The output filter largely controls these KD-5100 characteristics in most applications.
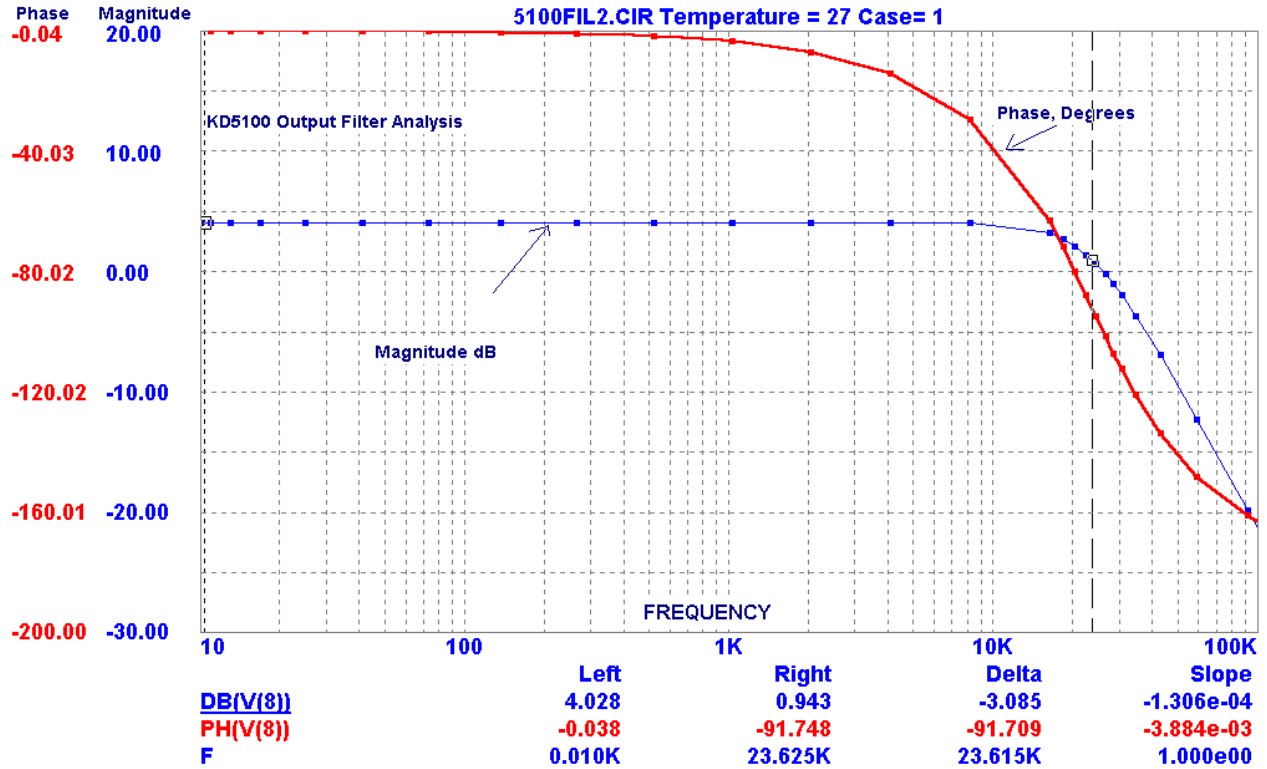
Output Filter Schematic
The output filter is a standard 2 pole Butterworth configuration. It is set for a cutoff frequency (-3 dB) of approximately 23 kHz.
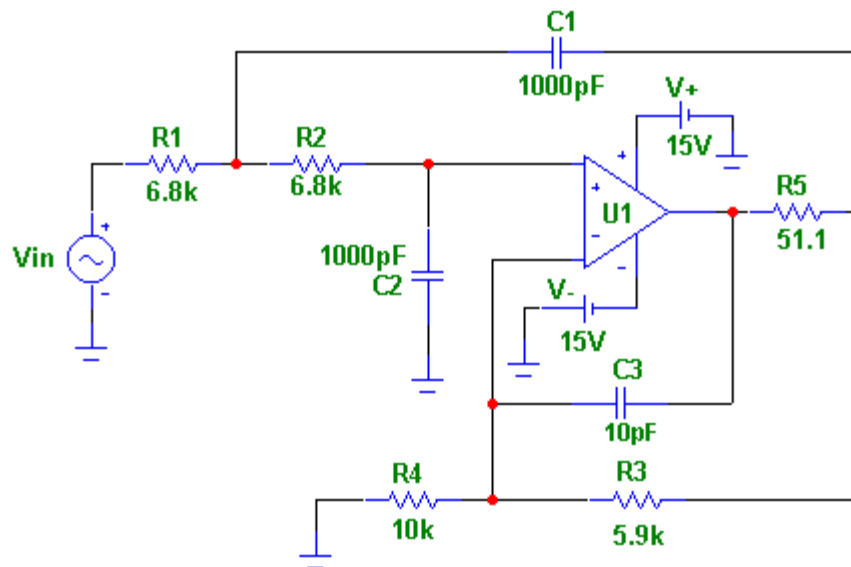
Output Filter Schematic

Analysis Results
The filter was analyzed using Micro-Cap V. The plot and table below show the magnitude (dB) and phase (degrees) output for the standard configuration in the KD-5100. The –3 dB point is at about 23 kHz. There is a small gain of 1.59 (about +4 dB) in the circuit.

5100FIL2.CIR Temperature = 27 Case= 1

KD5100 Output Filter Analysis

Phase, Degrees

Magnitude dB

FREQUENCY

	Left	Right	Delta	Slope
DB(V(8))	4.028	0.943	-3.085	-1.306e-04
PH(V(8))	-0.038	-91.748	-91.709	-3.884e-03
F	0.010K	23.625K	23.615K	1.000e00

Analysis Results of Magnitude and Phase vs. Frequency

Frequency, Hz	Magnitude, dB	Relative Magnitude, dB	Phase Shift, degrees
10	+4.03 dB	0.00	0.00
100	+4.03 dB	0.00	-0.36
1000	+4.03 dB	0.00	-3.50
2000	+4.03 dB	0.00	-7.01
5000	+4.02 dB	-0.01	-18.72
10000	+3.74 dB	-0.29	-38.8
20000	+2.17 dB	-1.86	-78.50
23600	+0.94 dB	-3.09	-91.71

Summary of Gain and Phase Characteristics of KD-5100 Output Filter