

LVR, a Novel Alternative for Linear Non-Contact Position Sensing in Harsh Environments

By
Leonard Goldman, PhD - Director of R&D
LRT Sensors
lengold@comcast.net

ABSTRACT

This paper is a description of the LVR sensor (Linear Variable Resonance), a new patented non-contact linear position sensor for use in harsh environments. The basic physics of the sensor involves a resonant circuit that converts linear motion into a digital output, eliminating the noise and temperature problems associated with all analog sensors. The design of the sensor allows all the electronic components to be at a remote location from the sensor itself. Because of these properties, this sensor can operate in various harsh environments of temperature, radiation, corrosion, and pressure. It currently has been tested at a temperature range of -70°C , up to 200°C , with options to operate at temperatures in excess of 1000°C . When compared to the LVDT, which is the current state of the art instrument for harsh environments, the LVR has better accuracy, a smaller envelope and most important, a much lower temperature sensitivity. The sensor is insensitive to electromagnetic radiation and strong magnetic fields. The measurement range of the sensor is from a few millimeters to over a meter in length while maintaining accuracy and reproducibility of less than 0.01% of full-scale.

INTRODUCTION

This paper will discuss the basic physics of the LVR sensor and its physical characteristics. Although the focus of this paper will be concerning the application of this technology to linear measurements, the same technology applies to rotary, gap and liquid level measurements. In Appendix A we discuss some new potential applications made possible by the new capabilities of the LVR.

FUNDAMENTALS OF THE LVR

The LVR differs from other noncontact sensors in one important aspect. All other sensor measurements rely on the amplitude of a generated signal, i.e. the output is analog. The LVR signal output is digital because it is based on a resonance phenomenon in the sensor.

The LVR sensor consists of a double coil wound on a round non-conductive ceramic tube. The insulated wire is wound as a helix with a large pitch. Upon reaching the end of the shaft, the pitch is reversed, and a returning helix is laid over the first coil. This is shown in Figure 1 below, where the enlarged view shows the position of both coils. The two ends of the coil are attached via separate coax cables to an electronics section located

outside the harsh environment zone where the sensor is located. The target rod would be attached to the object whose movement is being monitored.

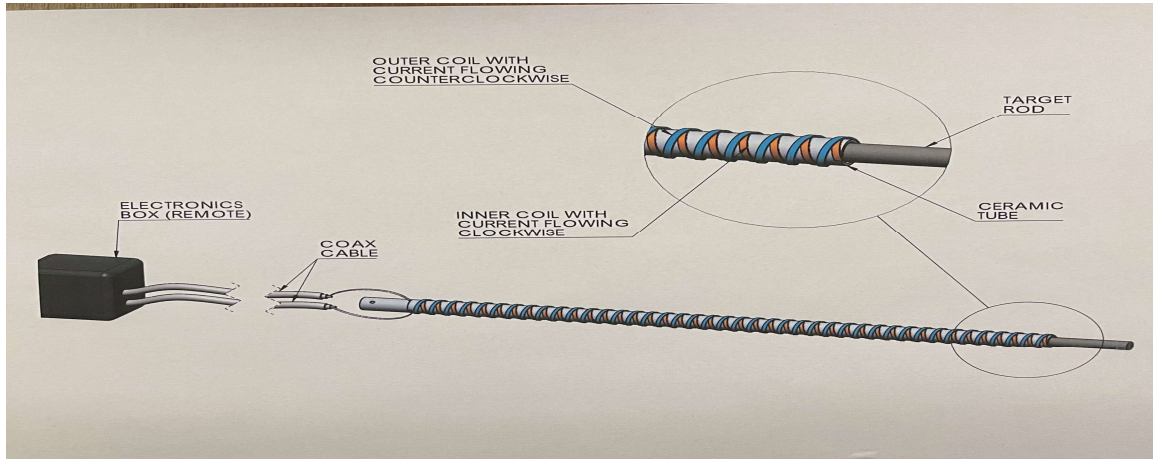


Figure 1

The electronics section completes an electronic LC resonant circuit whose frequency is determined by the equation in Figure 2 below.

Resonant Frequency Formula

$$f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}}$$

where 'f' = frequency in hertz
'L' = inductance in henrys
'C' = capacitance in farads

Figure 2

It should be noted that this equation for frequency does not depend on the resistance of the coil. An increase in the wire resistance with temperature will reduce the amplitude of the signal. So long as the amplitude remains above the threshold of detection, there is no effect on the value of the frequency. This will be discussed further in the section on temperature sensitivity.

Returning to the sensor, the two coils are now wired in series with current flowing clockwise in one coil and counterclockwise in the other. The electric and magnetic fields of these two coils are in opposite directions and thus to first approximation cancel each other. The net field outside the coil is 0 if the speed of light is infinite. Since we are dealing with reality, we find that the returning signal on the second coil is out of phase from the initial signal. The phase change is determined by the length of the coil which depends on the number of turns and the diameter of the coil. In other words, how much time does it take to go all the way down the coil and then back to the same location.. Thus, we do not get a total cancellation of fields, but we do get an external field that depends on this delay time which in turn is related to the position on the coil. If this field encounters a conductive surface, it will change the inductance and capacitance of the coil which in turn changes the frequency. The response is shown in Figure 4 below to be an almost perfect quadratic curve that is only a few percent deviation from linear. This output can be easily mapped to give a very accurate linear response.

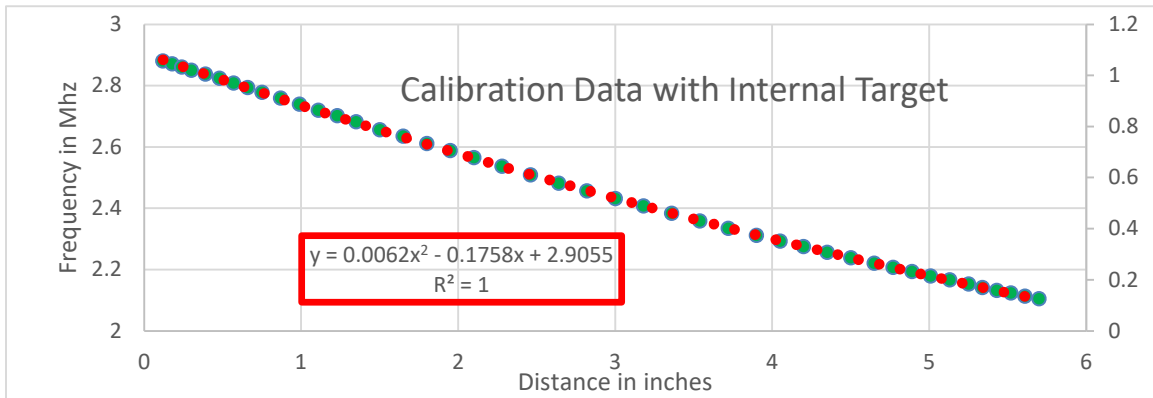


Figure 4

The coils are located inside the harsh environment with the coax cables connecting them to electronics located outside the harsh zone. Electronics completes a resonator circuit using the induction and capacitance of the coils to produce a frequency signal in the low MHz region.

This frequency is then converted to a digital signal with a single chip frequency meter. This digital value is then passed on to the microprocessor which converts the data to an analog or digital signal of the true position of the metal rod.

The block diagram for the LVR sensor is shown below in Figure 5

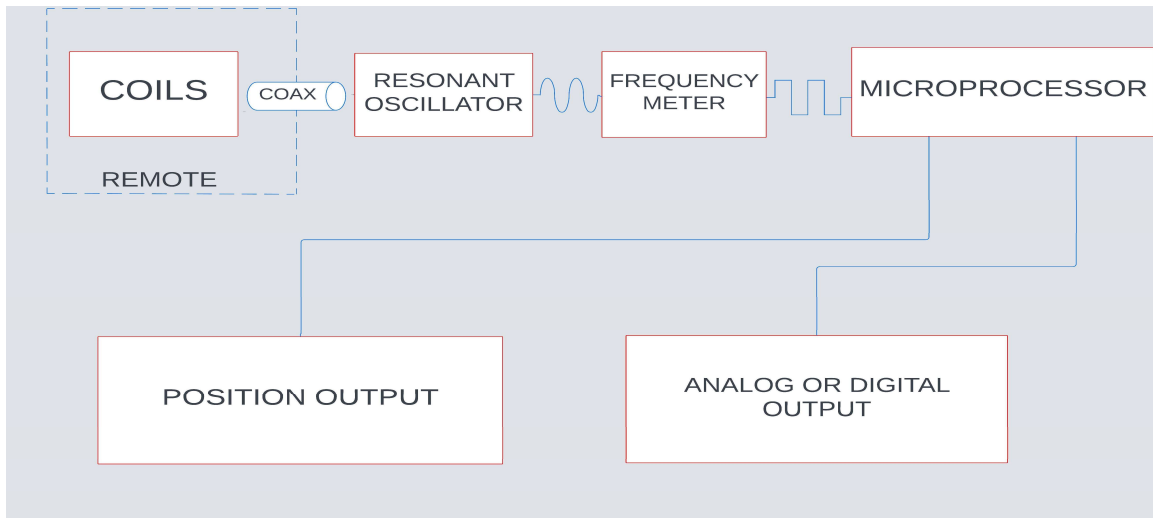


Figure 5

The frequency output vs position is a quadratic equation that deviates only a few percent from a linear result. The microprocessor then uses an algorithm based on the quadratic equation to correct the final output. The result is an accuracy of 0.01% FS(Full Scale).

Having a digital rather than an analog signal has many advantages. As mentioned earlier the frequency is not affected by the resistance of the wires in the coil. This translates into a low temperature coefficient for the sensor. There is still a small temperature effect due to the physical expansion and contraction of the coil and target rod. The frequency output is dependent on the gap between target rod and the coil as shown in Figure 6 below. (This frequency dependence is the basis for using this technique for measuring a gap.)

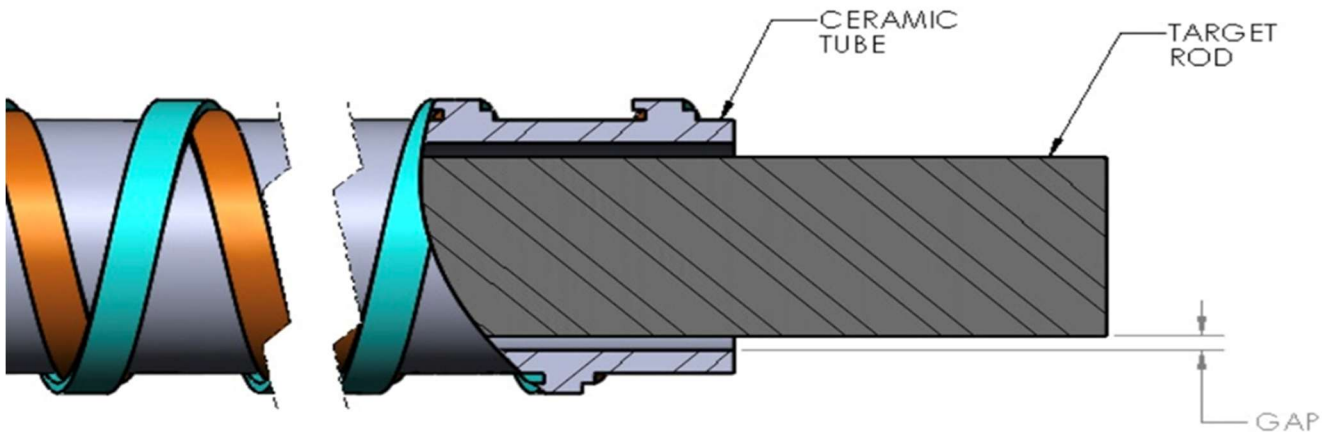


Figure 6

Although metals expand faster than ceramics, the diameter of the metal rod is smaller than the diameter of the ceramic tube and it is the product of diameter time the coefficient of expansion that determines the growth of the two objects. The use of Titanium and Aluminum Oxide eliminates the change in gap with temperature (there are many other metal and ceramic combinations available). This translates into an output change of less than 0.1% FS (or <3ppm/C) over the full range of -70 to 200 C. as shown in Figure 7 below.

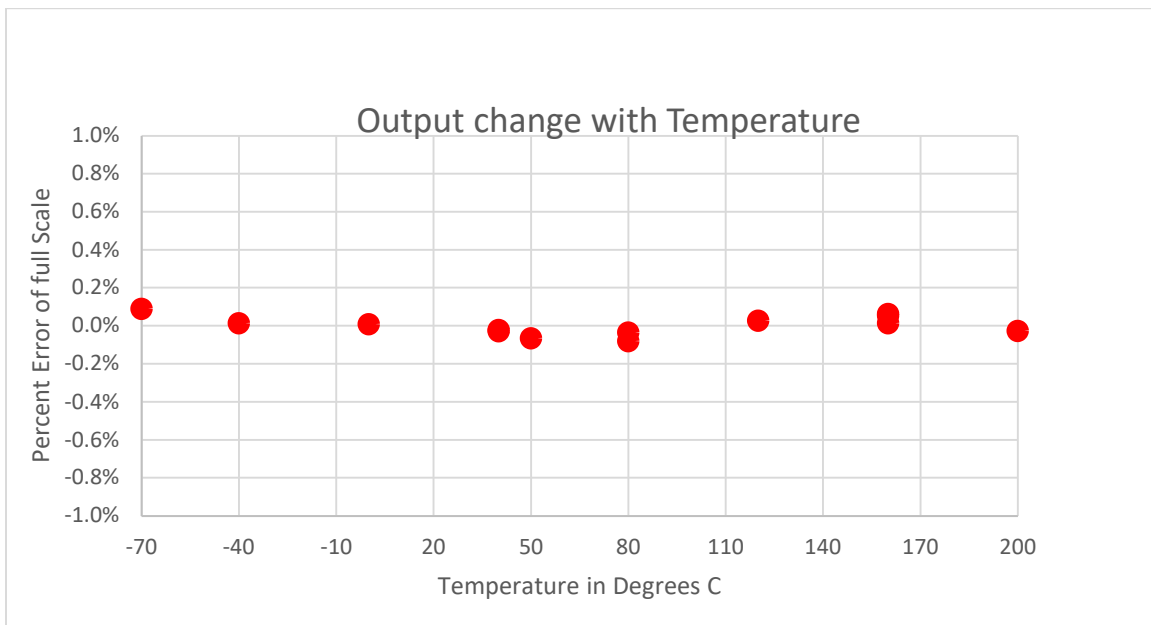


Figure 7

Although we only show data up to 200C, the sensor coil components are rated to 450C, and we are awaiting installation of a facility to make the higher temperature measurements. If the coils are wound with ceramic insulated wire the upper limit for operation is extended to 1000C. Even higher temperatures, as found in a Kiln, can be achieved by using refractory metals.

COMPARISON OF LVR VS LVDT SENSORS

The LVDT (Linear Variable Differential Transformer), is a 100-year-old non-contact inductive sensor technology that operates in harsh environments. It is a variable transformer with a movable magnetic core as shown in Figure 8 below.

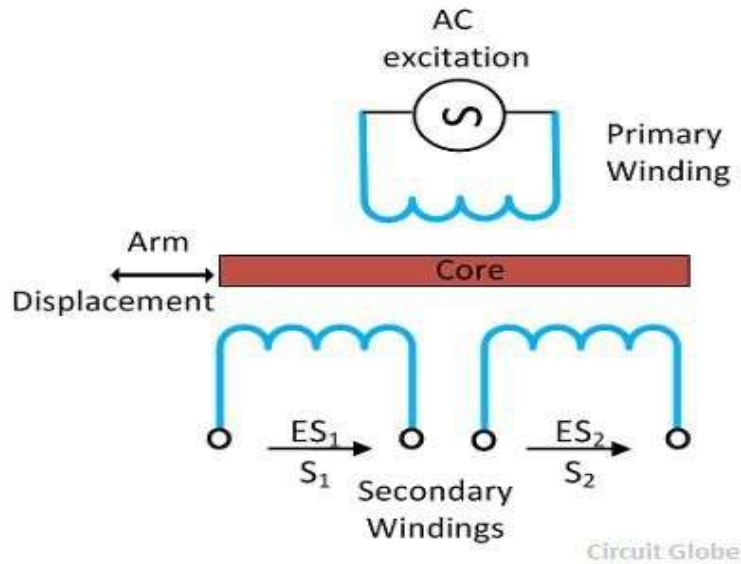


Figure 8

A carefully calibrated AC voltage is injected into the primary coil and then transferred to the secondary coils via the coupling of the moveable magnetic core which is usually a soft iron rod. As the core's position changes, the output voltages in the secondary coils change thus producing a measure of position. Typical signals from the LVDT are shown below in Figure 9 below.

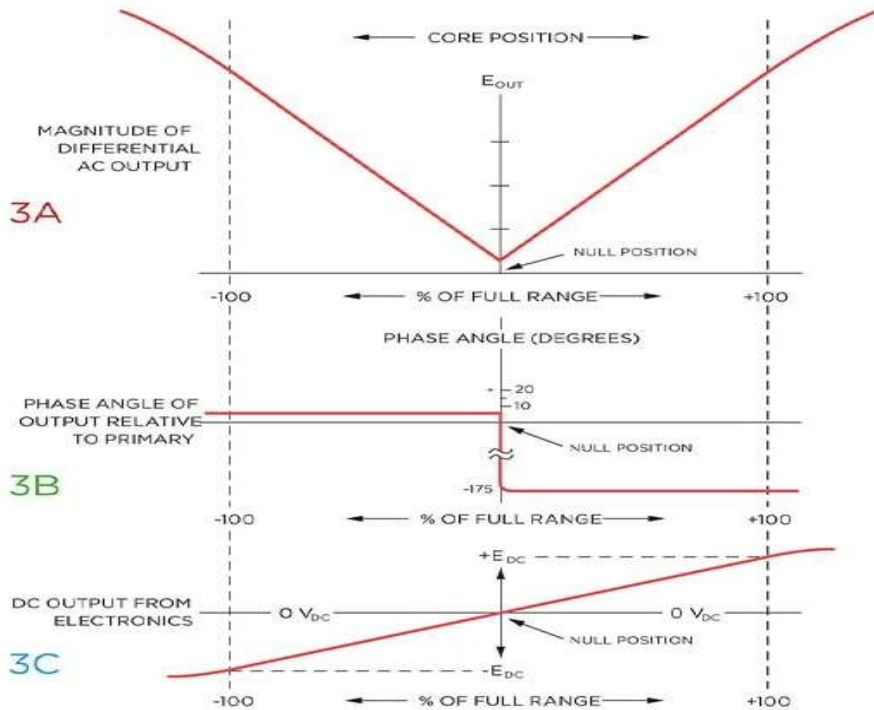


Figure 9

The two secondary coils are wound in opposite directions which produces the voltage signal in 3A. The remote electronic module measures these outputs and locates the null position at the midpoint of the sensor by measuring phase angles(3B). It then inverts the voltage of the signal below the null point to produce the final linear voltage output as shown in 3C. Electronics must compensate for all the voltage and phase changes due to resistance changes in the wire of the coil and the leads leading to the remote electronics. With proper compensation the temperature effect of the final output can be reduced to 50 ppm/C at the null point and an accuracy of 0.25%FS. However, away from the null point both parameters degrade.

This remote electronic module allows the LVDT coil to operate in temperatures up to 200°C. Both the wires and coils must be shielded from external magnetic fields. Since the output signal from an LVDT is analog, system noise limits its ultimate resolution.

The following table in Figure 10 below is a comparison of LVDT and LVR parameters.

	LVR	LVDT
Fundamental Output Signal	Digital	Analog
Operating Temperature Range (°C)	-70 to 200 C Optional to 450C Potential of >1000C	-55 to 200 C
Stroke to Length	2:1	3:1
Resolution	.001% FS	.1% FS
# of Wires to Electronics	2	4 or 6
Accuracy (Full-scale)	0.01% FS	0.25%FS
Temperature Sensitivity	<3ppm C	>50 ppm C
Requires Shielding from External Magnetic Fields	No	Yes

Figure 10

CONCLUSION

In conclusion, the LVR is a major improvement over existing noncontact linear sensors such as the LVDT. Its output is digital, not analog, and therefore insensitive to noise, attenuation, and temperature. The electronic components of the LVR can be in a remote area away from any hazardous conditions providing exceptional tolerances to extremes of temperature, radiation, pressure and chemical attacks. Its accuracy and resolution are better than any comparable absolute linear sensor. These characteristics along with its compact size make the LVR an excellent candidate to replace LVDT's in most applications. The expanded range and performance of the LVR versus an LVDT also opens the possibilities of new applications, two of which are described in the attached appendices. We welcome any inquiries to the contact information listed below.

Leonard Goldman, PhD
lengold@comcast.net
610-348-0677

APPENDIX A JET Engines

In jet engines there are conflicting requirements for the optimum size of the gap between the tips of the compressor blades and the outer housing of the engine. The smaller the gap, the higher the efficiency of the compressor. However, too small a gap risks contact between the rotating blade and the housing. Currently this gap is measured only when the engine is not operating.

The LVR technology can be configured as a gap sensor. This is accomplished by winding two flat coils as shown in figure 1 below. The coils are placed one on top of one another separated by a ceramic insulator. The assembly is then cased in a ceramic housing. Since the coils are wound in opposite directions the current flowing through the coils as part of a resonance circuit will have the same canceling effects seen in the linear sensor. The frequency of the resonant circuit using such coils will be dramatically affected as a conductive surface approaches the face of the coil. This produces an accurate measurement of the distance between the conductive surface and the coil, the definition of a gap sensor.

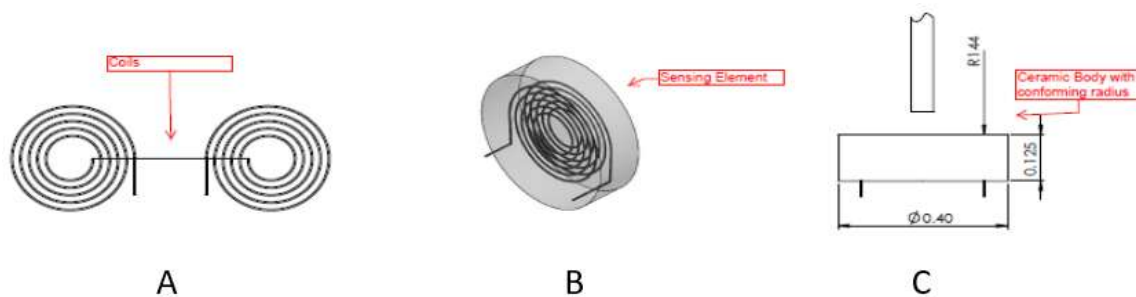


FIGURE A.1

From left to right:

- A. Diagram of windings of conductive coils
- B. Sensing element of stacked conductive coils encased in ceramic body
- C. Sensing element encased in jet engine wall with compressor blade in proximity

The coil must be made from a refractory metal such as tungsten or platinum to survive the high temperature environment of a jet engine. The assembly is configured to fit in the wall of the housing of the jet engine with cables connecting it to a remotely placed electronic package.

It is calculated that using a coil diameter of 10 mm and a gap of 5 mm there will be a change in frequency of 400 Hz for a 25 μm change in the gap. Because the bandwidth of the LVR is several MHz, it can be used to measure the gap of each turbine blade tip as it passes during operation of the jet engine. This could be valuable by allowing a smaller gap (more thrust) and a reduction in the time between ground maintenance inspections since this measurement would be made while the engine is in operation.

Appendix B **Monitoring Ceramic Part Size in a Kiln**

Ceramic parts are made by molding fine ceramic particles with a binder (usually a wax or oil) into a fixed shape and then firing the molded part at a high temperature. During the firing process, the part shrinks as the binder boils off and the ceramic particles fuse together eliminating the spaces between them. Complete shrinkage is critical to producing good parts and incomplete firing will produce defective parts. When developing a firing pattern for a certain ceramic part, tests are done to see how much time and temperature are needed to produce the fully fused part. Because temperature cycle times for firing range from several hours to several days, these are long and laborious tests. Even when completed, firing schedules are usually extended to ensure that full shrinkage has occurred.

The LVR could measure the shrinkage by installing a simple spring-loaded plunger to measure in real-time the shrinkage. The mechanical parts of the sensor (spring, target tube, etc.) would have to be made from a refractory metal but such machine parts are routinely used in high-temperature ovens. The ability to determine that a part has fully shrunk would offer significant economic saving for ceramic manufacturers. Use of the LVR would allow manufacturers to shorten or even eliminate much of the experimentation and reduce cycling times. There is no product available today that can make this kind of measurement at these elevated temperatures.