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Conf-940431--3

UCRL-JC-116930
PREPRINT

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This paper was prepared for submittal to the
American Society for Precision Engineering Conference
Tucson, Arizona April 6-8, 1994

April 1994

Lawrence Livermore National Laboratory

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LLNL/Lion Precision LVDT Amplifier

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Abstract

A high-precision, low-noise, LVDT amplifier has been developed which is a significant advancement on the current state of the art in contact displacement measurement. This amplifier offers the dynamic range of a typical LVDT probe but with a resolution that rivals that of non contact displacement measuring systems such as capacitance gauges and laser interferometers. Resolution of 0.1 µin with 100 Hz bandwidth is possible. This level of resolution is over an order of magnitude greater than what is now commercially available. A front panel switch can reduce the bandwidth to 2.5 Hz and attain a resolution of 0.025 µin. This level of resolution meets or exceeds that of displacement measuring laser interferometry or capacitance gauge systems. Contact displacement measurement offers high part spatial resolution and therefore can measure not only part contour but surface finish. Capacitance gauges and displacement laser interferometry offer poor part spatial resolution and can not provide good surface finish measurements.

Machine tool builders, meteorologists and quality inspection departments can immediately utilize the higher accuracy and capabilities that this amplifier offers. The precision manufacturing industry can improve as a result of improved capability to measure parts that help reduce costs and minimize material waste.

Introduction

This paper discusses the LVDT amplifier that was designed as part of a Cooperative Research and Development Agreement (CRADA) between Lawrence Livermore National Laboratory (LLNL) and Lion Precision a Division of Automated Quality Technologies. The Technology Transfer to Industry (TTI) program sponsored by the Department of Energy (DOE) provided the means to implement the CRADA with Lion Precision for the commercialization of the amplifier. Industry benefits because they receive technology available at LLNL and LLNL benefits because it now has a commercial source for these high-precision, low-noise amplifiers. LLNL designed the amplifier with requirements input from LLNL and Lion Precision and Lion Precision agreed to market and package the amplifier for sale. (See figure 1.)

This paper also presents a discussion of contact versus non-contact displacement measuring systems, the LVDT, the LVDT probe and an air bearing LVDT, and some application of these sensors at LLNL. Desirable characteristics of a LVDT amplifier are also included.

Contact vs. Non-contact Displacement Measurements

Measurement of precision machined parts and metrology measurements made at LLNL are done by using both non-contact and contact based displacement measuring systems. The most common non-contact displacement measuring systems in use are capacitance gauges and laser interferometers. The most common contact based displacement measuring systems are LVDT based.

Capacitance Gauge (Non-contact Sensor)

Capacitance gauges can be used as probes for part inspection or as feedback sensors for machine control as in the control system of the Large Optics Diamond Turning Machine (LODTM). A capacitance gauge is made from one or more capacitors. A capacitor is simply two conductors separated by an insulator. The equation for capacitance is;

$$C = eA/d \qquad (1)$$

e   is the dielectric constant of the insulator, usually air
A   is the area which is common to both conductors
d   is the distance between the conductors.

Capacitance gauges measure displacement by solving for (d) in equation (1). A single capacitor system will require electronics to linearize the output. A double or differential capacitance gauge system can be configured to provide a linear output as a function of displacement. Advantages of capacitance gauges are extremely good displacement resolution for part figure measurements that approaches the atomic diameter level (0.3 nm) and because they are non contact based sensors there is no part deformation. Disadvantages of capacitance gauges are; probe travel is typically limited to a few thousands of an inch with reasonable probe diameters, the probe must be kept normal to the part surface or a displacement error will result, and as can be seen from equation (1), the capacitance gauge is an area averaging device and therefore high part spatial resolution for surface finish measurements is not possible. Also, the material under inspection must generally be conductive and grounded and finally the dielectric must be constant i.e. the part should be clean and free of oil and contaminants.

Displacement Measuring Laser Interferometry (Non-contact Sensor)

Displacement measuring laser interferometry is an optical and electronic method for measuring displacement. An AC or heterodyne interferometer system is preferred over a DC interferometer because it translates the displacement information to a higher frequency band for increased accuracy, reduced noise and repeatability. The following is a simplified theory of operation. Two collinear orthogonally polarized different frequency beams of light originate from a laser that is typically a HeNe with a wavelength (λ) of approximately 25 μin. A portion of this laser beam is diverted and passed to a detector. The detector is a fast photo diode plus a focusing lens and a polarizer that is at 45 degrees relative to the plane of polarization of the beam. This polarizer causes the two beams to mix creating a beat frequency that is sensed by the detector. This beat frequency or difference frequency is known as the reference frequency and is generally 2 or 20 MHz depending on the laser manufacturer. The non-diverted portion of the laser beam passes through an interferometer where one polarization of light passes through a fixed path length in the interferometer. The other polarization leaves the interferometer and is reflected off a corner cube or a plane mirror that is located on the object whose distance is to be measured. This beam then returns to the interferometer where it recombines with the fixed path beam. A detector mounted on the output of the interferometer with a polarizer at 45 degrees to the plane of polarization of the beam will sense a phase change with respect to the reference frequency as the object whose distance to be measured is changed. A doppler shift in frequency occurs when the object is in motion. The two types of return mirrors, mentioned above, along with the laser wavelength determines the displacement resolution of the system. A corner cube or retroreflector system has an optical resolution of $\lambda/2$ and a plane mirror system has an optical resolution of $\lambda/4$. Commercially available interferometer electronics can then be used to extend this resolution by a factor of 128. It is therefore possible with plane mirror interferometers to achieve a displacement resolution of $\lambda/512$ or 0.05 μin.

The advantages of displacement measuring interferometry are the resolution and dynamic range it provides. A dynamic range of several feet with the above mentioned resolution is possible and is in use on LLNL's LODTM. However, some of the disadvantages are; it is an optical measurement and is typically used only for machine control and metrology measurements with a known return mirror. Direct part inspection is normally not possible due to beam alignment, part contour and part finish. Also, to obtain accuracy and the above resolution, it is important to minimize index of refraction changes along the path length and polarization mixing of the two different frequency beams. Alignment is important to minimize cosine error and maintain overlap of the two polarized beams recombining in the interferometer. Polarization mixing can cause a periodic error in the displacement measurement. It is related to alignment and the quality of the optical components. Another disadvantage to this system is that it is a relative displacement measuring system and can only measure displacement from a starting position.

LVDT Sensors for Displacement Measurement (Contact Sensor)

Electrical Characteristics

Linear Variable Differential Transformers (LVDTs) are used as contact based sensors for precision displacement measurement. An LVDT is a magnetic induction transducer with a primary winding, a movable magnetic core, and two secondary windings symmetrically spaced from the primary. A stylus, held in contact with a part to be measured, is mounted on a shaft extending from the magnetic core. (See figure 2.). The movement of the core causes changes in the magnetic coupling of primary to secondaries and induces a voltage in each secondary proportional to the core location. Connection of the secondary windings, in series opposing, will generate a null or zero-volt signal at the core center position where equal coupling exists into each secondary. This core null position is stable and repeatable and allows the LVDT to be an absolute positioning sensor. Any deviation of the core from the null will generate an abrupt change in phase of the secondary signal with respect to a reference signal, generating a linearly increasing voltage as the core is displaced from center. (See figure 3.) The LVDT operates on the principle of magnetic coupling; resolution is essentially infinite and depends on the signal-to-noise ratio of the signal conditioning electronics. Additional information on the electrical characteristics follows in the section; The Amplifier and Desirable Amplifier Characteristics.

Mechanical Characteristics

An LVDT is technically the transformer and the moveable magnetic core. Generally the term LVDT or LVDT probe as referred to in the literature is the transformer, the mechanical housing, the shaft that extends from the magnetic core, a radial bearing for the shaft and a stylus that mounts on the workpiece end of the shaft. The housing of the LVDT probe is held in a fixture that may be part of a structure or mounted on a moveable part of a machine e.g. one of the machine slides. Axial movement of the shaft is free within the mechanical constraints of the housing and is sensed as discussed under electrical characteristics. An important consideration of the LVDT probes includes the stylus force applied to the part under inspection. Most LVDTs require the part to support the full force of the stylus, shaft and core weight. This can result in part deformation at the point of contact and lead to incorrect displacement measurement when high precision is required. Use of the probe at any angle other than normal to the surface of the part is another important consideration because a lateral deflection force on the shaft/stylus exists that can lead to an axial movement component and therefore an error. This error is minimized by having high shaft bearing stiffness.

LVDTs are contact displacement measuring devices so it is possible to measure part contour figure and measure part surface finish. Part surface finish measurement requires high part spatial resolution which is a function of the stylus tip. This ability to measure part surface finish is one of the advantages of this type of sensor over capacitance gauges and laser interferometers.

Air Bearing LVDTs

An air bearing LVDT provides the ultimate in mechanical configurations. It provides essentially a friction free movement in the axial direction providing non-stick operation when high precision and repeatability are required. It also provides, high shaft radial bearing stiffness that reduces lateral deflection errors. To minimize part deformation, adjustment of stylus force to 0.1 gram is possible with this type of probe. Another consideration in the use of the probe, is to deflect the air exhausted from the probe away from the surface of the part to be measured to minimize the Joule-Thomson effect. LLNL has built air bearing probes with super invar housings and Zerodur shafts for the ultimate reduction in temperature induced errors.

Application of LVDTs at LLNL

There are many applications of LVDTs and air bearing LVDTs in use at LLNL. Principle applications include machine tool metrology, CMMs, inspection machines, tool set stations, diamond turning machines, roundness gauges, diamond tool mapping and precision manufacturing. Parts made at LLNL by machines such as the Large Optics Diamond Turning Machine, typically require the ability to measure part figure to better than 1 μin and part surface finish to better than 0.05 μin.

The Amplifier and Desirable Amplifier Characteristics

This amplifier is a precision high-gain, low-noise instrument designed to work with LVDT sensors for precision contact displacement measurement. The amplifier provides resolution an order of magnitude or better over similar amplifiers with a reduced level of sensor excitation. LVDTs are specified with a nominal linear range of travel of ± X inches, then a sensitivity of secondary volts per primary volts of excitation per core displacement. Effective resolution of the amplifier is equal to probe sensitivity times amplifier gain times volts of primary excitation resulting in volts per displacement. At the highest gain range of this amplifier, with a ± 0.020 inch LVDT, the effective resolution of the amplifier is 0.5 volts per microinch.

Small levels of primary excitation of the LVDT minimize probe heating, decrease thermal distortion of a part and provide higher measurement precision and repeatability. Constant current excitation of the LVDT maintains the same voltage across the primary coil; hence the same level of coupling is provided to the secondaries even if the coil resistance should change because of temperature changes.

An oscillator provides a fixed frequency, highly stable LVDT primary winding excitation or carrier signal. This carrier is coupled to the secondaries and amplitude modulated by the core position. The signal is then AC amplified and demodulated with a phase sensitive detector, obtaining the magnitude of displacement and sign data about the core null position. This signal is then low passed filtered to remove the carrier, providing a bipolar output with respect to the null position. Maximum frequency response or bandwidth of the amplifier is a function of the frequency of excitation of the sensor and the low pass filter setting. The output bandwidth is front panel switch selectable in this amplifier and is set for desired signal vs. noise performance.

The heart of the amplifier is a phase sensitive detector. This kind of detector has excellent signal to noise rejection. It will pick out a signal hidden by high levels of noise. The detector is driven with two signals. The input signal (the amplified secondary signal) and a reference signal derived from the oscillator. The output is a function of the input signal amplitude and the cosine of the phase between the input signal and the reference signal. Phase adjustment for maximum detector sensitivity is automatically done in this amplifier. Manual adjustment is done in other amplifiers with this type of detector. Incorrect phase adjustment can lead to errors and decreased amplifier sensitivity.

Systems of this type take information at a low frequency band and translate it to a higher frequency band to minimize the effects of noise. Since these systems have a carrier frequency, it is possible for two independent units to have slightly different carrier frequencies. Unless perfect shielding exists between the two units, a small signal from one unit may couple into the other unit through e.g. the sensor's cable and create a beat frequency. This beat frequency may show up as a slow drift or an erratic reading in the displacement measurement depending on the difference in the two units' frequencies. This amplifier prevents this condition because it provides for master-slave operation i.e. all amplifiers operate off a common frequency carrier.

The signal from the LVDT is composed of two components: the desired displacement signal and the undesired constant amplitude quadrature signal. The amplifier cancels this undesirable signal and allows maximum predetector gain and minimum post detector gain. High post detector gain can lead to output drifts because of electronic thermocouple effects and excess amplifier 1/f noise.

This amplifier offers four front panel selectable gain ranges, analog and digital front panel (F.P.) displays, two channel operation, arithmetic output that includes peak and valley detectors for maximum (max.) minimum (min.) and total indicator runout (TIR), autotuning, quadrature cancellation, offset adjustment, output polarity select, overload detectors, separate bipolar outputs analog ± 10 volt outputs for channel A, channel B and arithmetic output, F.P. selectable bandwidth and English/Metric (ENG/MET) settings.

Summary

In conjunction with an LVDT, this amplifier provides ultraprecision contact displacement measurements . It defines the state-of-the-art in contact displacement gauging. Using a typical probe with $\pm$ 0.020 inch of travel, it can resolve to 0.1 μin with 100 Hz bandwidth. Resolution to 0.025 μin is possible with a reduction in bandwidth to 2.5 Hz. It achieves this level of resolution with a sensor excitation that is approximately 5 to 10 times smaller than similar products.

This amplifier and sensor combination allow resolution equal to greater than non-contact capacitance gauges, but the combination provides a dynamic range (measurement range) which is typically 10 times that of a capacitance gauges with the stated resolution. The amplifier can exceed the displacement resolution of commercial displacement interferometry, but the dynamic range is limited to that of the probe travel. Contact displacement measurements with LVDTs provide high part spatial resolution and can measure both part figure and surface finish.

Acknowledgments

I thank Gary Armstrong and Ross Castleton of LLNL and Don Martin of Lion Precision for their effort in negotiating the CRADA. Special thanks for Gary Armstrong for starting the project and for project management and Ross Castleton for his support. I would also like to thank Bob Donaldson and Jim Hamilton of LLNL for their support during the amplifier design and development. Also, thanks to Ray Herbst of Lion Precision for his valuable technical input.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

References

1. Donaldson, R.R. and Patterson, S.R., "**Design and Construction of a Large , Vertical Axis Diamond Turning Machine,**" Proceedings SPIE, Vol. 433, August 1983, pp. 62-67

2. Hewlett Packard, "**Lasers and Optics,**" HP Application Note 197-2.

3. Zygo Corporation, "**ZMI-1000 Measurement Board,**" Operation Manual, August 1992.

4. Herceg, E.E., "**Handbook of Measurement and Control,**" Schaevitz Engineering, Handbook HB-76 Copyright 1976.

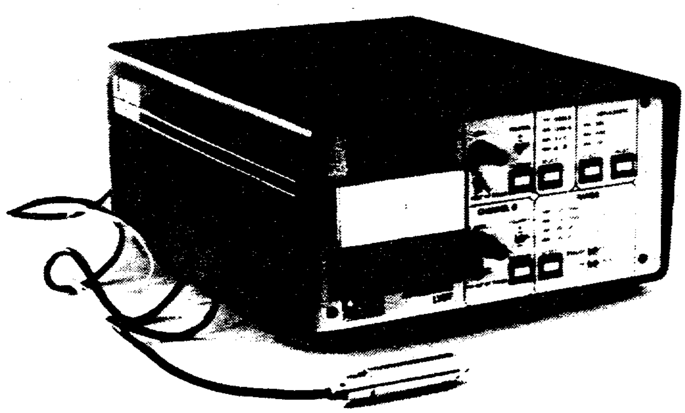

Fig. 1 The LLNL/Lion Precision Amplifier with an air bearing LVDT probe.

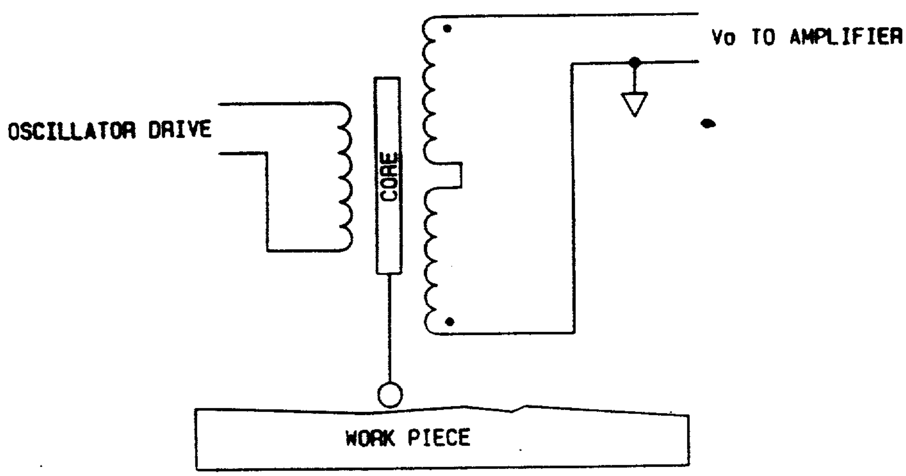

Fig. 2 Schematic drawing of the LVDT.

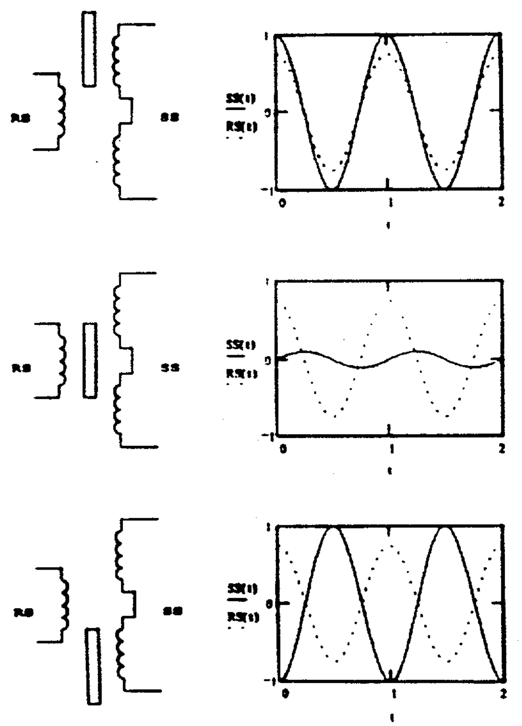

Fig. 3 This shows the LVDT secondary signal (SS) at three core positions. It also shows a special condition where no phase shift exists between the primary winding and the secondary windings. With this condition, the primary excitation and the detector reference (RS) are the same.