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# Development of Displacement Measurement Circuit of Linear Variable Differential Transformer

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***Abstract*— This paper presents development of displacement measurement circuit of Linear Variable Differential transformer (LVDT) using commercially available signal conditioner AD598. The objective of the work proposed is to design the external parameters such as resistance and capacitance to be connected with AD598 integrated circuit. The circuit is used to measure the displacement value of the core in terms of voltage with zero offset. The input to LVDT is given with DC variable supply in which AD598 with its internal oscillator converts to AC and further processing of output signal happens with the developed circuit. The LVDT requires AC input as it works on the principle of electromagnetic induction principle of a transformer. The measurable voltage signal will be of small magnitude with noise content in it which is eliminated with ratio metric measurement and filter circuit. With the proposed design components non linearity of less than 0.25 % is achieved. Application of the developed circuit was used in fatigue test controller to operate in displacement mode.**

***Index Terms*— Linear Variable Differential Transformer (LVDT), signal conditioning, calibration, magnetic interference, Non-linearity.**

## I. INTRODUCTION

A device that converts a physical quantity to an electrical signal is referred to as transducer generally used in majority of measurement systems. The physical variables such as mass, pressure, force and volume etc are measured using displacement. The Linear Variable Differential Transformer is one of the commonly used displacement transducer which is a low power consumption device known for its accuracy, infinite resolution, good linearity and good repeatability. Some conventional transducers are potentiometers, capacitance sensors and Hall effect sensors are also used to measure displacement. This sensor is used widely because of its contact-less sensing and infinite resolution. The Linear variable differential transformer patented by G. B. Hoadley in 1940 is commonly referred as LVDT. Linear variable differential transformers are used in the applications such as medical prostheses, orthodontics, automotive industry, seismic measurements, aircraft materials testing laboratories, and in many other applications.

The majority of research being done on LVDT are areas such as non-linearity measurement and its compensation techniques to extend the range of measurement. Single layer Functional Link Artificial neural network model is adopted to compensate the nonlinearity measurement of LVDT[1].Development of signal conditioning circuits is one of the requirement of processed output signal of transducer. The linearity is dependent on factors such as

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transducer geometry, primary and secondary winding, variation in input frequency, current or voltage quality of core material. A dual secondary winding [2] constructional change has better performance as compared to conventional type of LVDT. The dual winding compensation technique introduces a marginal change in coil dimensions. cost and weight of the assembly.

A phase difference exists between the signal applied to the primary and signal resulting from the difference of two secondaries. If input applied signal is normalized cosine cos(ωt), the low pass filter input signal y(t) is given by

$$y(t) = S * x(t) * \cos(\omega t + \Phi) * \cos(\omega t)$$

where S is LVDT sensitivity and x(t) is the displacement. CosΦ dependence can be avoided with in frequency domain. Goertzel algorithm [3] is applied and carrier frequency is used as a function of sampling frequency and obtained 0.5% Full Scale measurement error which is within the limit of LVDT. The shortcoming of the approach was dependence on phase difference of primary and secondary voltage signals.

DSP based Signal Conditioners proved better frequency response and better electrical noise characteristics [4]. DSP based signal conditioning with modified Costas receiver showed better performance even during the noise test applied to LVDT. Least Mean Square method of signal processing of LVDT resulted better than other differentiated approaches[5].

These electronic circuits perform any one of the following functions: amplification, level shifting, filtering, impedance matching, modulation and demodulation. Further work resulted in the commercially available signal conditioner such as AD 598 and AD 698 which are based on the ratio metric method of secondary signals. The ill effects caused due to the phase shifts of primary and secondary do not influence on the circuit performance. The advantage of AD598 signal conditioning IC eliminates the problems of obtaining constant amplitude and constant frequency as it works on the ratio of the difference and the sum of the LVDT output signal. A fuzzy proportional-integral- derivative controlled analog circuit was developed for sensitivity measurement of LVDT without losing the range of measurement [6]. The linearity performance of signal conditioning systems was observed using 4 wire and 5 wire LVDT's and comparison was made among the commercially available AD598, AD698 and Spectral Estimation DSP. Low cost 16 bit microcontroller with digital LVDT signal conditioner was used and obtained less error with five point estimator [7]. Sample hold circuits were replaced instead of Low Pass Filters in a simple signal conditioner which emphasized on low cost with simple configuration [8]. Phase locked loop was introduced in a demodulator circuit which acts as peak amplitude finder in linearity measurement of LVDT[9]

The non-linear behavior of LVDT can be due to many factors such as the constructional features including the number of turns of both primary and secondary winding and the environmental conditions. The transducers require calibration each time and hence a measuring technique was proposed using Artificial Neural Network which tested and validated for various physical parameters, excitation frequency and different temperatures eliminating the calibration of LVDT [10]. Further Optimized Artificial Neural Network was proposed to obtain the reduced percentage error as compared to the standard instrument error [11].

Major research on LVDT are based on Finite Element Analysis using FLUX Simulator whereas two inductive spiral coils having one stationary and the other moving was proposed and its performance analysis was done using COMSOL Multiphysics software. Spiral type coils showed significant accuracy of ±0.5% for 0.00635 mm step of displacement[12]. Based on magnetic equations and transformer theory a unique SPICE modeling[13] of LVDT is obtained. Finite Element Modeling of LVDT provides in depth understanding of magnetic processes and also provides quick and efficient way of changing the properties such as dimensions , material and geometry[14]. The geometrical to electrical parameters conversion was achieved as magnetic conductance are not measurable[15]. Analytical equations were solved using MATLAB integral equations and the results were verified with COMSOL computations[16].The FEMM model[17] with equal halves of secondary winding assuming symmetry has resulted in obtaining characteristics of output voltage with various parameters such as primary length, secondary length, core radius, core length, etc..

The transducer LVDT has many advantages, literature review has provided more information about the non-linearity, calibration, signal conditioning issues along with magnetic interference effects on the performance of LVDT.

The measurement of displacement is essential in finding the linearity error which is essential in selection of LVDT. Linearity error is typically expressed as +/- a percentage of full-range output (FRO) or in terms of an error band width that envelopes the straight line and deviations.

Remaining section of the paper is organized as follows. Section II presents the circuit description of Linear Variable Differential Transformer with necessary basic equations of induced voltage. Section III describes about a simple calibration circuit of LVDT with signal conditioning Integrated Circuit IC AD598. In Section IV, the observed displacement values and voltages as graphical representation is shown. Section V is conclusion.

## II. CIRCUIT DESCRIPTION

LVDT is a position-to-electrical sensor whose position voltage proportional to the position of a movable magnetic core. The core moves linearly based on the variation in mutual inductance between a primary and each of two secondary windings when a ferromagnetic core moves along its length. Usually both secondary windings are connected in series opposition as shown in Fig1.

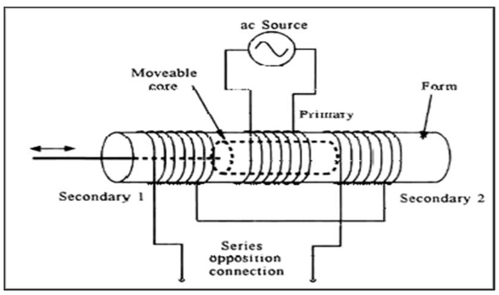


Fig 1. Winding diagram of LVDT

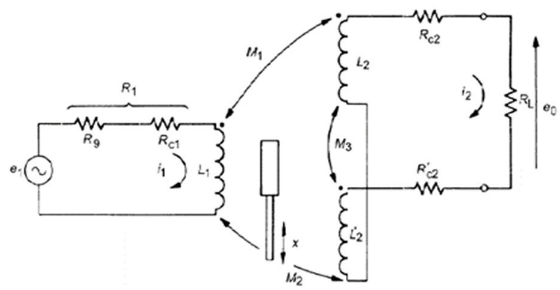


Fig 2 : winding digram of LVDT

In an LVDT which is also referred as an electro-mechanical transducer, has physical movement of the core detected as a change in magnetic coupling between the windings internally connected. When an input sine wave at a fixed frequency is applied a voltage is induced in the secondaries, two secondary voltages measured offers the difference and is linearly proportional to the core absolute position. Given the primary input signal f(t) with amplitude $A_p$ and frequency $f_0$ , $f(t) = A_p \cos 2\pi f_0 t$ the differential amplitude modulated secondary voltage y(t) can be expressed as $y(t) = A(x) \cos(2\pi f_0 t + \Phi)$where A(x) depends on the LVDT core position. The equivalent circuit of an LVDT is shown in fig.2. It consists of the secondary total resistance

$$R_2 = R_{c2} + R_{c2}' + R_L .......(1)$$

the induced emf

$$E_1 = I_1(R_1 + sL_1) + I_2(- s M_1 + s M_2) ......(2)$$

and of secondary

$$0 = L_1(-sM_1 + sM_2) + I_2(R + sL_2 + sL_2' - sM_3)...................(3)$$

The output voltage is given by

$$E_0 = I_2 R_L .............................(4)$$

In center position when $M_2 = M_1$ , $E_0 = 0$;

The relation between output voltage and core position depends on load resistance.If there is no load connected then $E_0$ reduces to $s(M_2 - M_1)L_1$ and $I_1 \approx \frac{E1}{sL1+R1}$ is the primary current which is approximately constant irrespective of the core position.

The output voltage E0 is directly proportional to difference in mutual coupling,M2 – M1 and hence to core position but it is 90° out of phase with respect to primary current. The sensitivity is dependent on excitation frequency and it increases with it.As load resistance increase, sensitivity also increase , but at certain frequency when phase shift becomes zero sensitivity decreases. The output signal is actually an amplitude modulated voltage even though the change in mutual imepdance is due to the result of displacement.

LVDTs are commonly used for measuring displacement and position. In feedback positioning systems these transducers are frequently used as null detectors in airplanes and submarines. The Measurement ranges are from ±100 mm to ±25 cm. The range of supply voltages are 1 V to 24 V, with frequencies from 50 Hz to 20 kHz. Sensitivities range from about 0.1 V/cm to 40 mV/mm for each volt of excitation voltage. Resolutions of even 0.1 mm are feasible.

A 4-wire or 5-wire configuration LVDT sensors are manufactured, in the former the signal at the output terminals is the difference of the secondary windings, in the latter the voltage at each secondary winding can be measured with respect to their connection point, provided as an additional output wire. The functions such as AC amplification, demodulation and low pass filtering are performed by traditional analog single chip solution devices which are available in monolithic form. These devices can also be built from discrete parts to tailor them to the specific application. Mixed signal conditioning modules offer different design solutions and interface options, for instance mixing an ASIC design with a microcontroller unit or using fast DSP processors to realize the LVDT reading algorithm[18]. The most common LVDT reading technique consists of a demodulation of the LVDT output obtained by multiplying a signal synchronous with the carrier.

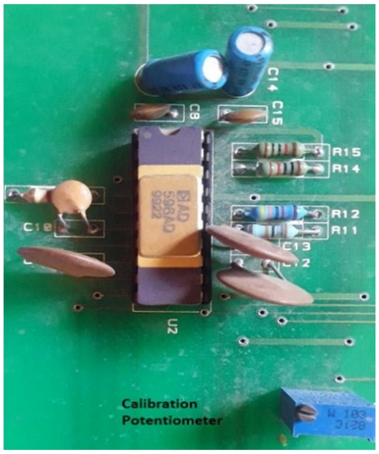


Fig 3: AD598 with components to measure output

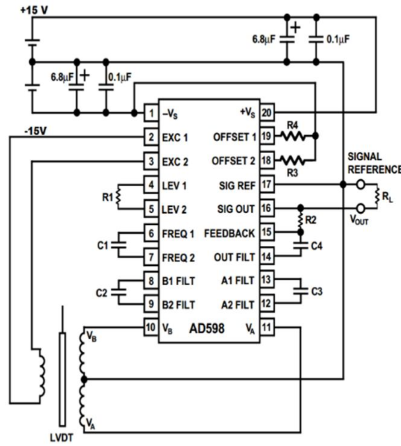


Fig 4. LVDT diagram with core.

## III. SIGNAL CONDITIONING CIRCUIT WITH DESIGNED COMPONENTS.

It is an excitation and amplification system for passive transducers. The excitation of +/- 15 DC supply Volts is given to the circuit and as per the connection details provided the LVDT is connected for measurement of core displacement.
LVDT primary is energized with AD 598 which produces secondary output proportional to the core position. Analog Devices[19] AD598 consists of a sine wave oscillator, precision rectifier demodulators, a ratio metric decoding scheme, and an output amplifier. One single resistor R1 determines the amplitude of the oscillator. The oscillator frequency can be programmed for any frequency between 20 Hz and 20 kHz by changing a single external capacitor C1. The AD598 provides an output which is proportional to the ratio of the difference divided by the sum of the LVDT secondary voltages. The LVDT characteristics offers certain limitations but amore temperature independent output is obtained. The circuit consists of an oscillator which produces a low distortion sine wave , frequency is determined by a single capacitor C1.The output of LVDT secondaries, ($V_A$-$V_B$) is proportional to core position.AD598 eliminates the problems of secondary phase shifts, production of constant amplitude, constant frequency excitation signal and compensating for the phase shifts as a function of temperature and frequency.

## IV. EXPERIMENTAL RESULTS

Steps of design procedure.
1. Select the excitation frequency say 2.5 kHz.
2. The component capacitor C1=0.01µF determines the excitation frequency.
3. Amplitude determined by R1 = 3.9K Ω
4. Capacitances C2=C3=C4 =0.4 µF & R3 =R4 = 10KΩ
5. R2 = Vout x ($V_A$+$V_B$) / (S x Vpri x 500µA x d)
Where Vout = 10 V Full Scale range(+/- 5V)
d = Full scale displacement
S = Sensitivity at Full scale
Data sheet provides d and S values, R2 value is calculated and obtained as 3.9KΩ.
If VA-VB/VA+VB = +/- 1 which is reference point to define offset and for span of Vout = +/- 10 volts
R2 = 20 K Ω.
6. Supply voltage is bipolar +15 V and -15V

The application of this circuit was used in controller of fatigue testing machine with LVDT of Transtek 0220-0000 and AD598 with above design.

Fig 5: one end of the core(+5 V)

Fig 6:Voltage 0V

TABLE I. MEASURED VALUES OF DISPLACEMENT

| Measured voltage in volts | Measured Displacement (mm) |
|---|---|
| -5.04 | 258 |
| -4.02 | 230 |
| -3.03 | 205 |
| -2.03 | 180 |
| -1 | 154 |
| 0 | 129 |
| 1.01 | 101 |
| 2.02 | 77 |
| 3.03 | 51 |
| 4.0 | 26 |
| 5.01 | 0 |

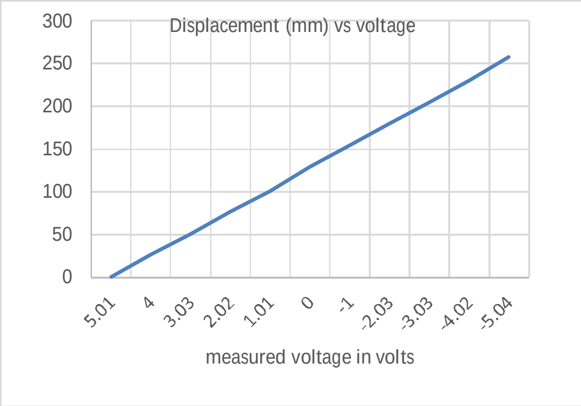


Fig 7:Realtionship between AD598 Output Voltage and displacement

Fig 5 & Fig 6 shows the measured value of displacement and voltage which indicates zero core position and mid position of the core respectively. The value of R1 decides the amplitude of the input voltage and C1 is the only capacitor which decides the excitation frequency required to supply to the input. The measured values are shown in the table.

## V. CONCLUSION

The output of LVDT is obtained with signal conditioning IC AD598 circuit having ratio metric measurement. The additional circuitry provided with components of resistors and capacitors has made easy to measure accurately. Calibration Potentiometer provides the zero setting of the voltage and observed a non-linearity error of less than 0.25%. The components are low cost and a simple design of the circuit provides easy accessibility with reliable output. The performance of the circuit is confirmed by experimental implementation. A digital read out [20]with minimized noise is the future scope of work.

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