THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Design of Linear Variable Differential Transformer (LVDT) Based Displacement Sensor with Wider Linear Range Characteristics

K. I. S. Baidwan
Student, Department of Electronics Engineering, Defence Institute of Advanced Technology, Pune, India
C. R. S. Kumar
Associate Professor, Head of the Faculty, Electronics & Engineering Department,
Defence Institute of Advanced Technology, Pune, India

Abstract:
The linear variable differential transformer (LVDT) is widely used in industrial and defence applications for online dimensional measurements. Its basic structure consists of a primary coil and two secondary coils like an electrical transformer. It works on the principle of variation of mutual inductance between a primary winding and two secondary windings with a movable magnetic core. The core is moved by a nonmagnetic rod connected to a measurement device. When the core is at null position and the primary winding is given an alternating voltage, the voltages induced in the centre of each secondary winding are equal and therefore no output is produced at secondary side. However, while the core moves from its central null position, one of the two induced secondary voltages increases and the other decreases by similar amount. The output voltage of secondary is proportional to the displacement of magnetic core. As LVDT is a physical transducer, therefore, its performance is based on its design and dimensional features. Eash transducer as per its design parameter will have a defined linear range of operation. This paper presents a design model of a solenoid LVDT for simulation on MATLAB and mainly emphasis on achieving an optimum design for increasing the linear range of operation of the LVDT based displacement.

Keywords: Primary winding, secondary winding, linear range, magnetic core, transducer

1. Introduction

The Linear Variable Transformer Differential (LVDT) is a displacement sensor widely used in industrial and defence sectors as part of the physical measurements system. The basic structure of LVDT consists of a primary coil and two secondary coils like an electrical transformer. However, LVDT has a movable magnetic core that when is moved from its null position, it varies the mutual inductances among secondary coils and the primary coil. It is applied an AC voltage E i/p, in the primary coil, as shown in Figure below. The secondary coils are connected in series with opposing phase, so when the magnetic core is exactly at the physical centre between them, then the output voltage Eo/p is zero, as the net output is the difference between the two secondary voltages, Eo/p = E 01- E02. If the core is moved from the centre, then due to imbalance of magnetic flux intensities between the primary coil and the secondary coils an output voltage that is proportional to the core displacement is produced. This imbalance produces non-zero output voltage proportional to the core displacement.
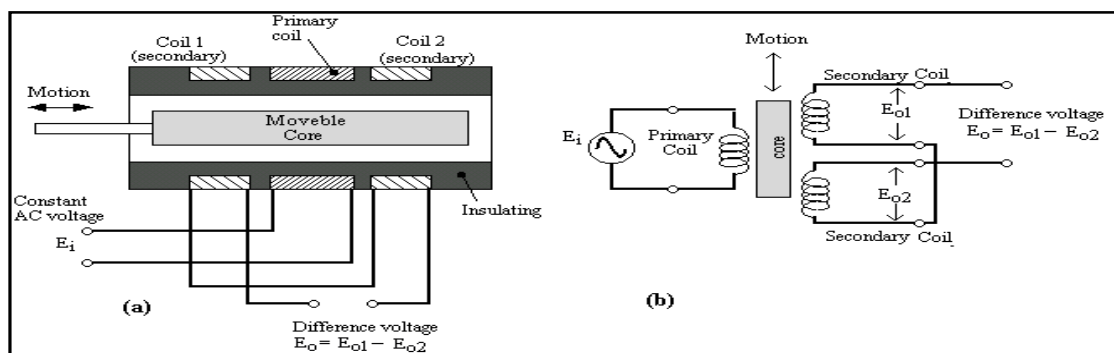

Figure 1: LVDT: (a) Internal Construction. (b) Electrical Diagram

2. Literature Survey

As LVDT output is a nominally linear function of core displacement within its linear range of motion, a plot of output voltage magnitude versus core displacement is essentially a straight line. Beyond the nominal linear range, the output begins to deviate from a straight line into a gentle curve leading to non linearity. Linear Variable Differential Transformer (LVDT) plays an important role to measure the displacement in various control system applications. Due to non linearity in output, the sensor is effectively being employed only in the linear range of operation. Therefore, if a sensor is used for full range of its nonlinear characteristics, accuracy of measurement is severely affected.

A lot of attempts have been made in the past to increase the linear range of operation of LVDT. The nonlinearity compensator designed by [1] uses the artificial neural network to overcome the non linearity in the output characteristics of LVDT. However, the proposed model involves high computational complexity. Also, in [2] the authors present a technique of dual secondary coils for self compensation of LVDT. Some DSP techniques have been employed in LVDT to achieve optimum result to overcome non linearty problem circuits [3][4]. The simple solution to overcome nonlinearity has also been achieved in [5] by square coils in which the core moves perpendicular to the axis instead of along the axis.

The paper mainly emphasis on increasing the linear range of operation of LVDT by simulating the Electrical and Physical parameter based model (Cleonilson Protásio de Souza1, Michel Bruno Wanderley, IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements) of LVDT in MATLAB. The aim is to achieve an optimum design for implementation with wider linear range characteristics, keeping in mind the static characteristics like sensitivity, accuracy and precision of the transducer.

3. Modeling of LVDT

A   Linear Variable Differential Transformer can be modeled in two ways, i.e Electrical parameter based model and geometrical parameter based model (Cleonilson Protásio de Souza1, Michel Bruno Wanderley, IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements). The electrical Parameter based model uses electrical parameters as resistances and inductances, and Geometric Parameter based model uses geometrical parameters based on the physical dimensions of the LVDT. The paper aims to allow interaction of electrical parameter based model with physical parameter based model to bring out an optimum design of LVDT.

3.1. Electrical Parameter Based Model

The Electrical Parameter based model uses all the electrical parameters as resistances and inductances to define the model. We can define and derive the Electrical Parameter based model of the LVDT by referring the figure 2 below, where, Rp is the total resistance of the primary coil, $Rs1$ and $Rs2$ are the resistances of the secondary coils, LP is the self-inductance of the primary coil, $Ls1$ and $Ls2$ are the self inductances of the secondary coil, and $M1$ and $M2$ are the mutual inductances between primary coil and the secondary coils. Considering Rs as the total resistance of the secondary circuit, where, $Rs = Rs1 + Rs2 + RL$ and RL is a load resistance.

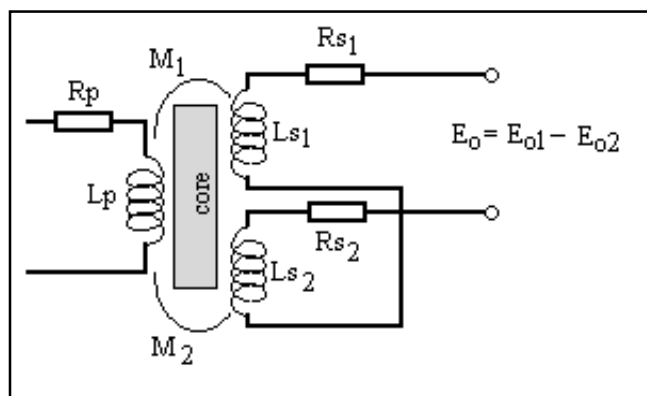*Figure 2: Electrical Parameter Based Model*

3.1.1. The Induced Voltage in the Primary Coil Is Given By:-

E i =R p I p +sLp I p + s(M1 I s – M2 I s)   (1)

where *M1, M2* are dependent of the core displacement and Ei, the excitation voltage. The net equation in the secondary circuit is given by:-

s(M1 I p − M2 I p) +I s Rs + s(Ls1 I s + Ls2 I s) = 0   (2)

Also the Output voltage Eo/p = Is* Rload.

Equating (1) and (2) and solving as explained in [5] we can derive the Electrical parameter Based model as shown:-

Eo/p = Ei/p (Δm/Lp)   (3)

The above equation (3) gives use the intuitive feel of the basic opetaion of LVDT. The output voltage is propoptional to the difference in mutual inductance. Incase the core is not displaced from its null position, the Δm will be zero, thus no output voltage will be

produced at secondary of LVDT. However, in case the core is displaced from its null position, the output voltage at secondary coil will be propotional to the difference in mutual inductance produced due to core displacement.

3.2. Geometric Parameter Based Model

Geometric Parameter based model uses geometrical parameters based on the physical dimensions of the LVDT . The diagram below shows physical structure of an LVDT with its respective geometrical parameters. These parameters include No. of turns of primary coil **Np**, No. of turns of secondary coil **Ns**, length of primary coil **h1**, Length of secondary coil **h2**, external diameter of coils **D**, the core diameter **d**, length of core inserted in secondary coil 1 **t1**, length of core inserted into secondary coil 2 **t2** and $\partial 1$, $\partial 2$ are the air gaps as shown in the figure.
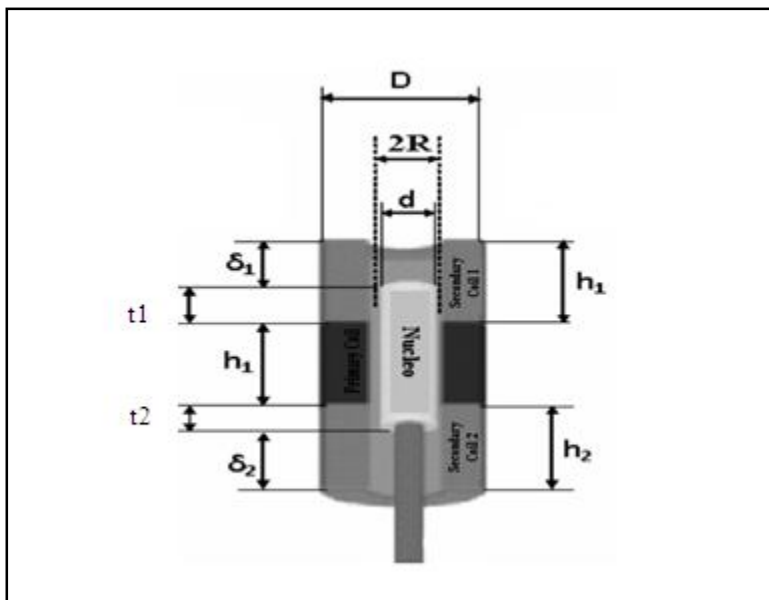

Figure 3: Geometric Parameter Based Model

3.2.1. Magnetic Circuit Theory

As explained (in Cleonilson Protásio de Souza1, Michel Bruno Wanderley, IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements], Magnetic conductance plays an important role in defining the geometric model of an LVDT. Magnetic conductance depends on the geometry and the permeability of the circuit. It is obtained from cross sectional area penetrated by magnetic fields, mean length of magnetic field lines and magnetic free space permeability. The magnetic conductance can be defined as:-

Magnetic Conductance = G = $(\mu o\, \pi\, R^2)/\, \partial 1$

Magnetic flux produced by the primary coil can be divided into two main paths. The first path passes through the air gap of the end faces of the magnetic core and the magnetic shell, this is called the main flux 'Φo'. The second path passes through the air gaps of the magnetic core sides, facing the two secondary windings and the magnetic shell, this is called the secondary flux 'Φs'.

As the structure of LVDT is symmetrical about its central axis, the conductance is parallel to each other and the total conductance can be written as:-
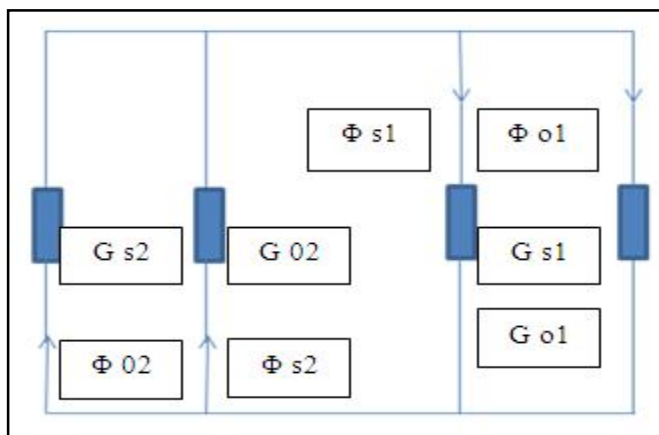
 G = (Go1+ Gs1)||(G02 + Gs2)

Figure 4 : Equivalent Magnetic circuit of an LVDT

Magnetic Conductance due to main flux (G01) = (μoπR^2)/∂1   (1)
Magnetic Conductance due to main flux (G02) = (μoπR^2)/∂2   (2)
∂1 = h1 – t1, where t1 = t0 + ∂t   (3)
∂2 = h1 - t2, where t2 = t0 – ∂t , where ∂t is the steps or length of displacement (4)
Also, Magnetic Conductance due to secondary flux (Gs1) = (h2- ∂1)*g   (5)
Magnetic Conductance due to secondary flux (Gs1) = (h2- ∂2)*g   (6)
where'g' is specific magnetic conductance between cylinderical surfaces [6] i.e g = 2μo π / ln (D/d)
The equation for self and mutual inductance can be derived from [6] and can be written as:-
Self Inductance : Lp= N^2/G   (7)
Mutual Inductance : M1 = (Np*Ns *g*t1^2) / 4h2   (8)
Mutual Inductance : M2 = (Np*Ns*g*t2^2) / 4h2   (9)

3.3. Electrical Parameters interms of Physical Parameters
On subsituting the values of self inductance in equation (8) and mutual inducatnce in equation (9) derived from the physical parameters based model above and merging the same in the electrical parameter based model ini equation (3), we can define the final equation for the output of LVDT as:-
Eo/p = Ei/p (Ns*g (t1^2-t2^2)) / 4(h2*Np*G)   (10)

4. MATLAB Code for Simulation of Output Charecterstics
Using the above equation in MATLAB, the designer can change various physical parameters and study the effect of any physical parameter on the output characteristics of LVDT. The code for output characteristics of LVDT with different number of turns for secondary coils **Ns** is shown below. Designer may change any other physical parameter study the change on output.

```
close all
clear all
E_in=5; % I/P voltage to the LVDT
N_sec=[100:400:1200]; % No of turns of secondary
N_pri=800;% No of turns of primary
% N_sec= 800%[600:200:800]; % No of turns of secondary
%N_pri=[600:200:800];% No of turns of primary
mu=4*pi*10e-7; % Value for absolute permeability
%mu=4*pi*10.^-7;
D=6; % dia of the winding in mm
d=3; % dia of LVDT core in mm
h2=50; % height or length of the secondary windings in mm
t0=5 ; % Length of core inserted into sec at null point in mm
R=5; % Radius of effectice flux in mm
del_t= [-10:5:50]; % Steps of displacement of core
t1= (t0+del_t); % length of core inserted into the secondary windings - up
t2= (t0-del_t);% length of core inserted into the Primary windings - down
del1= h2-t1; % Length of air gap - up
del2= h2-t2; % Length of air gap - down
G01=mu*pi*(R^2)./(del1); % Magnetic conductance due to primary flux - up
G02=mu*pi*(R^2)./(del2); % Magnetic conductance due to primary flux - down
g=(2*mu*pi)/(log10(D/d)); % Magnetic conductance for cocentric cylinders
GS1=(h2-del1).*g; % Magnetic conductance due to secondary flux - up
GS2=(h2-del2).*g; % Magnetic conductance due to secondary flux - down
G=(G01.^2+(GS1.*G01)+(G01.*GS2))./(G02+GS2+G01+GS1);
% G=((G01+GS1).*(G01+GS2))./(G02+GS2+G01+GS1);
for i=1:length(N_sec)
%for i=1:length(N_pri)
E_out(i,:)=E_in*(N_sec(i)*g*(t1.^2-t2.^2))./(4.*(h2*N_pri*G));
% E_out(i,:)=E_in*(N_sec*g*(t1.^2-t2.^2))./(h2*N_pri(i)*G);
end
figure(1)
for i=1:length(N_sec)
%for i=1:length(N_pri)
plot(del_t,E_out(i,:))
hold on
end
grid on
```

xlabel('Displacement of core in mm)')
ylabel('Output voltage of LVDT in volts')
title('Output voltage vs distance for varying secondary turns')

5. Simulation Results

The simulation result, showing the output charecterstics by changing various physical parameters of LVDT is shown in the figures below:-
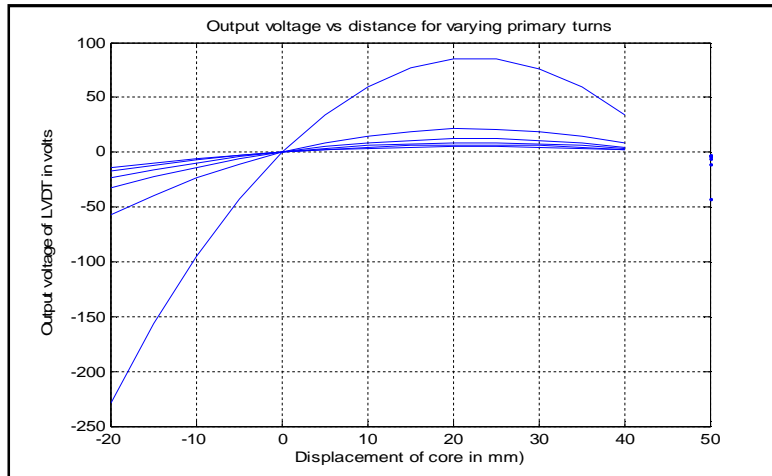
Figure 5: Output charecterstics of LVDT by changing number of Primary Turns
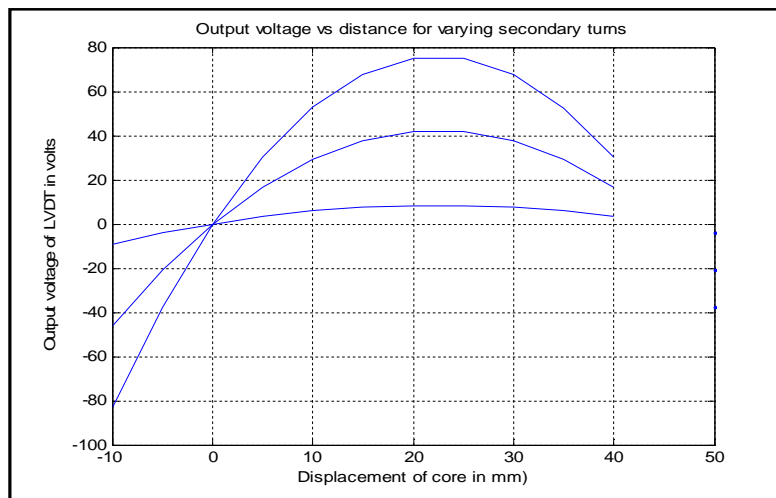
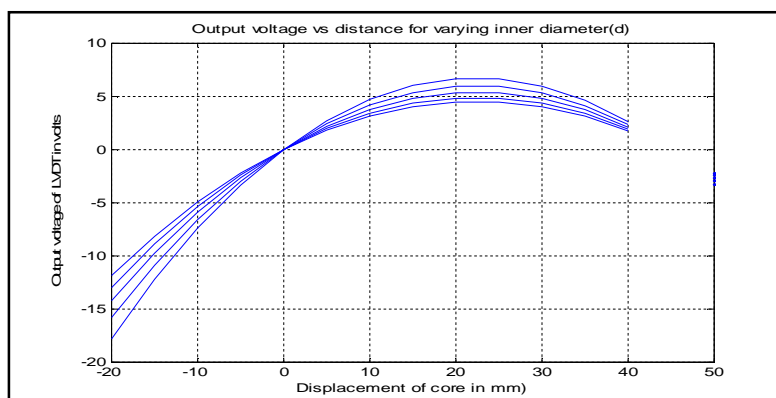*Figure 6: Output charecterstics of LVDT by changing number of Secondary Turns*

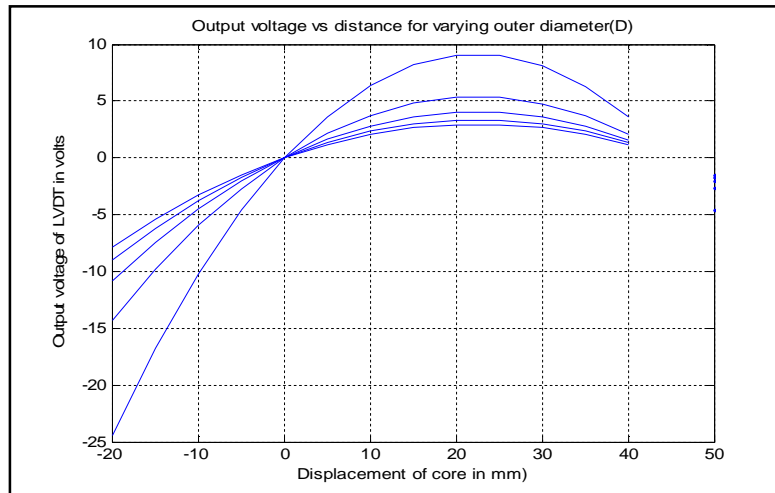*Figure 7: Output charecterstics of LVDT by changing the core Diameter*

Figure 8: Output charecterstics of LVDT by changing outer Diameter of coils

6. Conclusion

The equation for output of an LVDT can be used in MATLAB to simulate the output characteristics as shown in the simulation results above. The Designer can vary the various physical parameters like No. of turns of primary coil **Np**, No. of turns of scondary coil **Ns**, length of primary coil **h1**, Length of secondary coil **h2**, external diameter of coils **D**, the core diameter **d**, length of core inserted in secondary coil 1 **t1**, length of core inserted into secondary coil 2 **t2** and the air gaps $\partial 1$, $\partial 2$ to achieve an optimum result based on his requirement.

7. Acknowledgement

8. References

i. Saroj Kumar Mishra, Ganapati Panda, A Novel Method for Designing LVDT and its Comparison with Conventional Design. IEEE Transactions on Sensors Applications Symposium Houston, Texas USA, 7-9 February 2006 .

ii. S.C. Saxena, and S.B.L. Seksena, "A self-compensated smart LVDT transducer," IEEE Transactions on Instrum. & Measurement*,* Vol. 38, Issue: 3, pp.748 – 753, June 1989.

iii. G. Y. Tian, Z, X. Zhao, R. W. Baines, N. Zhang, "Computational algorithms foe linear variable differential transformers (LVDTs)" IEEE Proc.-Sci. Meas. Technol.*,* Vol. 144, No. 4,pp 189-192, July 1997.

iv. D. Crescini, A. Flammini, D. Marioli, and A. Taroni, "Application of an FFT-based algorithm to signal processing of LVDT position sensors" IEEE Transactions on Instrum. & Meas.*,* Vol. 47, No. 5, pp. 1119-1123 Oct. 1998.

v. Y. Kano, S. Hasebe, and H. Miyaji, "New linear variable differential transformer with square coils," IEEE Transactions on Magnetics, Vol.26, Issue: 5, pp.2020 – 2022, Sep 1990.

vi. Conversion from geometrical to electrical model of LVDT, Cleonilson Protásio de Souza1, Michel Bruno Wanderley, 16th IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements Sept. 22-24, 2008, Florence, Italy.