

Real Time Measurement of Position as well as Direction using Linear Variable Differential Transformer

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Abstract—

Linear Variable Differential Transformer (LVDT) is a transducer which converts mechanical displacement into output electrical corresponding to the input displacement. This paper describes the procedure of measuring displacement and the direction of the movable iron of LVDT. Normally this is impossible with conventional LVDT operation. The construction and working of the modified LVDT was explained. The results of the conventional LVDT and the modified LVDT were compared. The procedure to measure exact position and displacement direction of movable iron was given.

The magnetic field distributions of modified LVDT connections were analyzed using FEMM (Finite Element Method Magnetics) software. The analysis results were given and the corresponding density plots were plotted.

Index Terms — DC Conversion Circuit, Direction Measurement, LVDT, Position Measurement.

I. INTRODUCTION

LVDT is most widely used inductive transducer for translating the linear motion into electrical signal. Magnetic coupling between primary and secondary coils is established by using a soft and movable iron core. In normal LVDT both the secondary coils are connected in series opposition. However, the output voltage is zero. As the core moves up or down, the induced voltage in one secondary coil increases while that of the other decreases. Here the magnitude of the output voltage is in AC nature. In this case measuring both position as well as direction of movable iron is difficult.

Normally LVDT has one primary winding (P) and two identical secondary windings (S1, S2) wound over a hollow pipe of non-magnetic and insulating material and consists equal number of turns placed on each of the secondary windings. A soft iron is placed inside of the pipe. The direction of movement of the iron makes output voltage increases or decreases. If the soft iron moves in forward direction the output voltage is in phase. If the soft iron moves in backward direction the corresponding output voltage with 180 Deg out of phase [1]. In this case it is very difficult to

estimate the exact position and direction of movement.

It is clear that LVDT has limited range of displacement and range varies from $\pm 0.01\text{mm}$ to $\pm 0.25\text{mm}$.

II. REVIEW OF THE RELATED WORK

Linear Variable Differential Transformers (LVDTs) are devices for the measurement of distances. They are used to measure tiny to large ranges, from millionths of an inch to many inches. Thus, LVDTs not only sensitive and accurate in detecting mechanical motion, it is also sensitive to the direction of the motion. Since LVDTs are transformers and there is no electrical continuity between primary and secondary coils.

DLD series LVDT Demodulators [2] are developed for measuring position and direction of the movement. But it needs following equipment

1. Setting SPAN switches.
2. Setting SPAN potentiometers.
3. Offset the demodulator.
4. Determining electrical null.
5. Locate mechanical null and superimpose it with the electrical null.

This procedure is very difficult and time consuming. It requires skilled labour.

Linear Technology Corporation (LTC) developed a new LVDT signal conditioning which combines LTC1967 RMS to DC Converter with a separate phase detector circuit [3]. But it needs the following equipment.

1. OP-Amp circuits.
2. Phase lag compensators.
3. Phase modulators and comparators.
4. Bias setter.
5. Amplitude modulator.

Finally the output of this conditioner gives the information about the displacement (Amplitude) and direction (Phase) of the movable transformer core.

Hareem Tariq [4], have been developed low frequency damping sensors for seismic attenuation systems for gravitational wave interferometers and for mirror positioning. One type of these linear variable differential transformers has been designed to be most insensitive to displacement allowing 3D movement of the sensor to read precise position along the sensitivity. A second LVDT geometry has been designed to measure displacement of the vertical positions. But this

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system makes use of electronics and leads to the saturation problems.

All the above reviews lead to the modified form of the conventional LVDT to measure displacement and direction very precisely.

III. METHODOLOGY

A. Conventional and Modified LVDT connections

The conventional LVDT is shown in Fig. 1, it consists one primary coil excited by AC supply, two secondary coils and movable iron core.

By connecting AC voltmeter across the output terminal of the LVDT, an RMS voltage proportional to the displacement will be displayed (that do not have polarity), not direction.

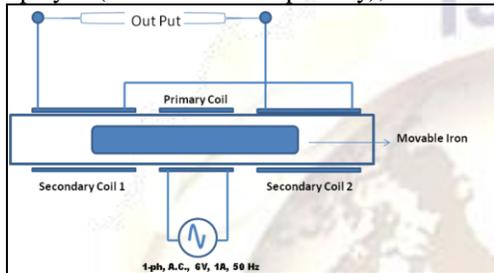


Fig.1. Conventional LVDT with back to back connection of secondary windings.

Both direction and displacement can be measured by using rectified output with the modified design as shown in Fig. 2.

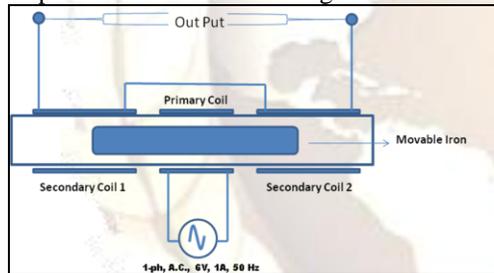


Fig.2. Modified LVDT with series connection of secondary windings.

B. Design of Modified LVDT

Design constraints are mainly to limit construction effort and use easily available materials. The number of turns in primary is 100 and each of the secondary consists 200 turns with double layer winding. 1/2" PVC pipe was used to wound the coils and a section of 7/16" iron rod for core. Here 0.315 mm (30 SWG) insulated copper wire was used to wound the coils.

1. Design Specifications

- ID of the PVC pipe = 1.66 cm
- OD of the PVC pipe = 1.7 cm
- Resistance of 30SWG wire = 0.2212 Ohm/mm
- Diameter of copper wire = 0.315 mm
- Diameter of the core = 1.5 cm
- Material of the core = iron

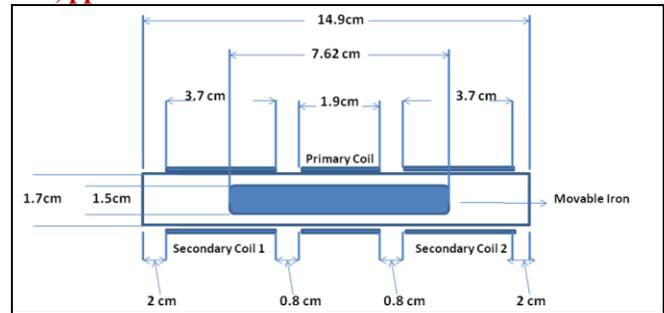


Fig.3. Modified LVDT connections with dimensions.

C. Working Specifications

1. LVDT Excitation (i/p) : 1-phase, A.C, 50Hz, 6V, 1A
2. Output Voltage Range : +2.61 to - 4.62
3. Zero Adjustment Range : ± 0.3 V
4. Linearity : $\pm 0.05\%$ of full scale
5. Operating Temperature : - 20 to 140 deg F
6. Power Consumption : 0.2212 watts

D. Working of the Modified LVDT

The position is indicated by the amplitude of DC voltage. The direction is indicated by polarity of DC voltage, how the positive and negative voltages are increasing and decreasing.

The block diagram shown in Fig. 4 describes the operation of modified LVDT.

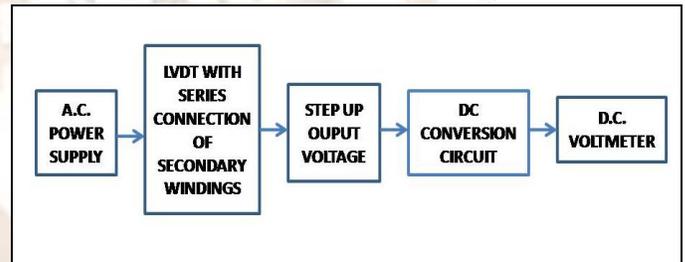


Fig.4. Block diagram shows the operation of Modified LVDT

1-phase, 230V, 50Hz, AC supply was given to the primary winding. Initially movable iron was placed at center position. The upper secondary winding terminals were named as 11 and 12. Similarly lower secondary winding terminals were named as 21 and 22. In modified LVDT, the 12 and 21 terminals were short circuited and the output was taken at 11 and 22 terminals. Here the short circuit is considered as neutral terminal (N) for step transformers and the upper terminal '11' is considered as phase for transformer '1' and terminal '22' was considered as phase terminal for transformer '2'.

The above connections can be observed from the Fig. 5.

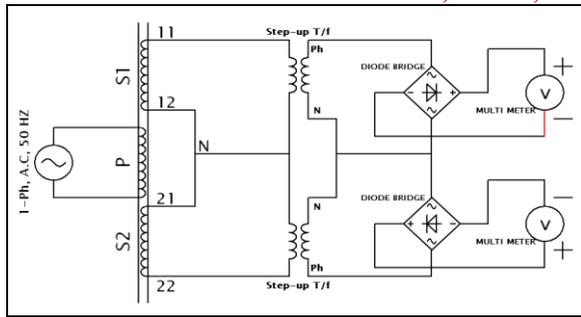


Fig.5. Modified LVDT working connections

The output terminals of upper transformer are connected to Diode Bridge to convert AC voltage to DC voltage, and this positive voltage can be measured by using normal multimeter. Similarly the same set-up was arranged for lower transformer. And the polarity of the voltage is negative. Hence the total voltage of these two voltmeters gives the voltage corresponds to the displacement of the movable iron.

1. Case ‘A’:

If the iron is placed in the forward direction, then, the voltage in the voltmeter ‘V1’ is high and the voltage in the voltmeter ‘V2’ is very low with negative sign. The sum is positive voltage.

2. Case ‘B’:

If the iron is placed in the backward direction, then, the voltage in the voltmeter ‘V1’ is low and the voltmeter ‘V2’ reading is high, and results negative voltage.

3. Case ‘C’:

If the iron is placed at the center position across the primary winding, then the reading of voltmeters ‘V1’ and ‘V2’ gets cancelled each other and resultant voltage is ‘zero’. This point is known as null position.

E. FEMM Analysis

Before going into the practical implementation of the modified LVDT operation, it is necessary to analyze the magnetic flux density distribution and the field intensity distributions across LVDT primary and secondary coils.

FEMM [5] is simulation software to design and analyse the flux and field intensity distributions for a low frequency electromagnetic problems on two dimensional planar and axisymmetric domains. The problem currently addresses linear magneto static problems.

Magneto static problems are problems in which the fields are time-invariant. In this case, the field intensity (H) and flux density (B) must obey

$$\nabla \times H = J \quad \text{-- (1)}$$

$$\nabla \cdot B = 0 \quad \text{-- (2)}$$

Subjected to a constitutive relationship between B and H for each material

$$B = \mu H \quad \text{-- (3)}$$

FEMM solves the above equations and shows the flux density and field intensity distributions. The following graphs were obtained for the modified LVDT with the following parameters.

FEMM problem parameters:

1. The entire problem is defined in ‘cm’.

2. Four blocks were considered for analysis of the magnetic field.
 - Air
 - Secondary Winding – 1
 - Primary Winding
 - Secondary Winding – 2
3. Secondary coils (1,2) with 200 turns.
4. Made up of Standard Wire Gauge (SWG) copper material.
5. Diameter of copper wire is 0.315mm (30swg).
6. Current flowing is 0A.
7. Primary winding coil with 100 turns.
8. Made up of Standard Wire Gauge (SWG) copper material.
9. Diameter of copper wire is 0.315mm (30swg).
10. Primary coil current is 1A.
11. Mesh size is 0.1.
12. ‘Prescribed A’ boundary conditions with zero quotients.

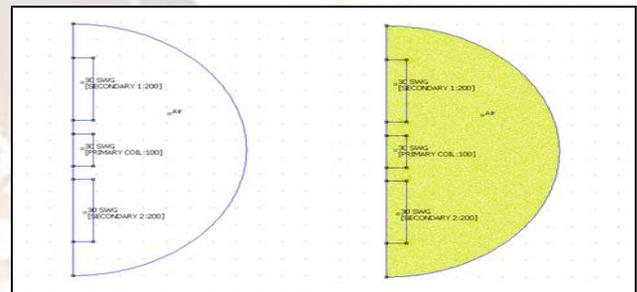


Fig.6. LVDT construction block with meshing.

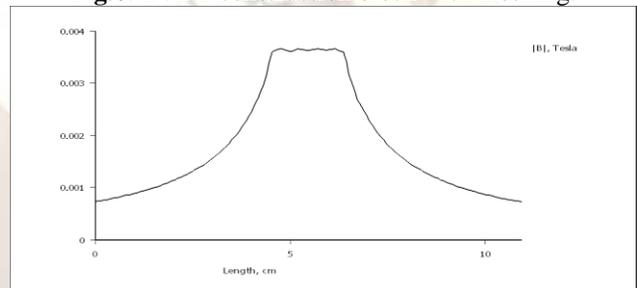


Fig.7. Distribution of flux density (B)

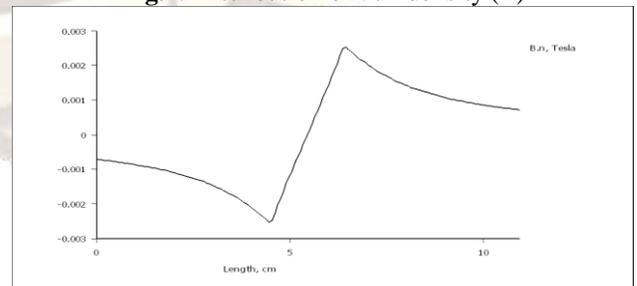


Fig.8. Distribution of normal flux density (B.n)

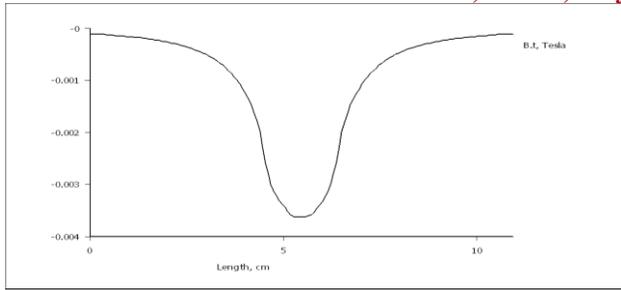


Fig.9. Distribution of tangential flux density (B.t)

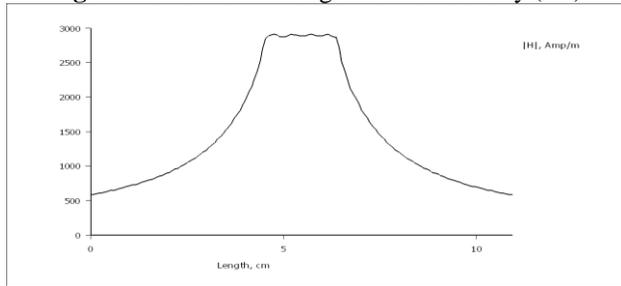


Fig.10. Distribution of field intensity (H)

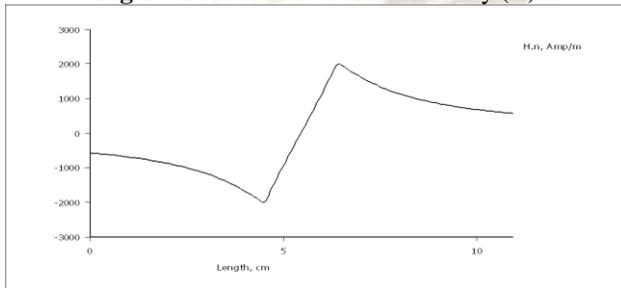


Fig.11. Distribution of normal field intensity (H.n)

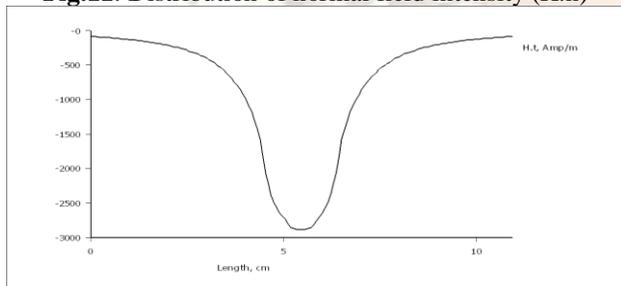


Fig.12. Distribution of tangential field intensity (H.t)

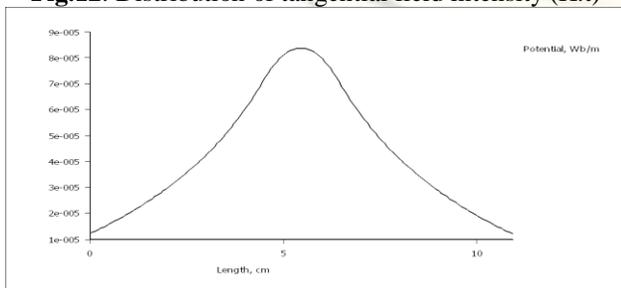


Fig.13. Distribution of potential

The below results confirms that the flux produced by primary links with the secondary windings.

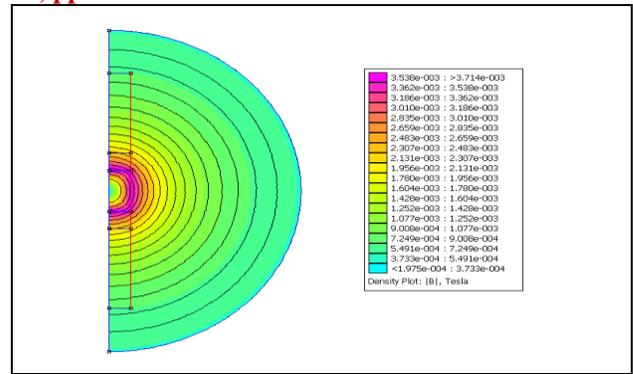


Fig.14. Density plot of magnetic flux density (B)

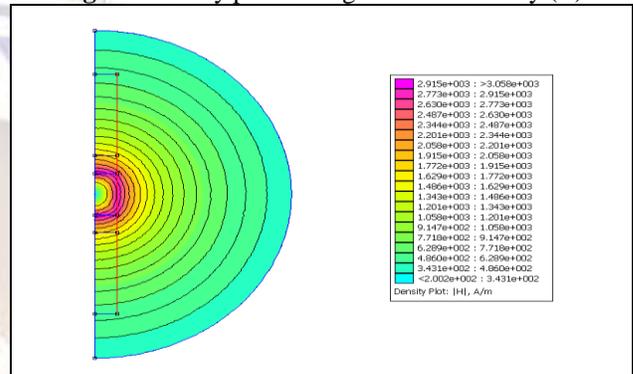


Fig.15. Density plot of magnetic field intensity (H)

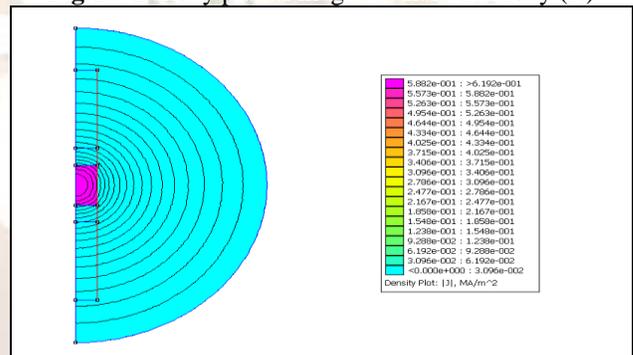


Fig.16. Density plot of current density (J)

The above results confirms that the flux produced by primary links with the secondary.

Primary Coil properties

- Total current = 1 Amps
- Voltage Drop = 0.221295 Volts
- Flux Linkage = 8.92566e-005 Webers
- Flux/Current = 8.92566e-005 Henries
- Voltage/Current = 0.221295 Ohms
- Power = 0.221295 Watts

Secondary Coil – 1 properties

- Total current = 0 Amps
- Voltage Drop = 0 Volts
- Flux Linkage = 6.12253e-005 Webers
- Power = 0 Watts

Secondary Coil – 2 properties

- Total current = 0 Amps
- Voltage Drop = 0 Volts
- Flux Linkage = 6.12254e-005 Webers
- Power = 0 Watts

Integral results on the LVDT coils surface

- Normal flux = 1.49822e-012 Webers
- Average B.n = 1.37451e-009 Tesla
- MMF drop along contour = -87.6404 Amp-turns
- Average H.t = -804.04 Amp/Meter
- Contour length = 0.109 meters
- Surface Area = 0.00109 meter^2
- Force in x-direction = -0.000142559 N
- Force in y-direction = 1.31232e-006 N
- Torque about (0,0) = 1.06174e-005 N*m
- Result = 2.21269e-007 Webers^2
- Average (B.n)^2 = 2.02999e-006 Tesla^2

F. Practical Implementation

The step by step implementation of the modified LVDT is given below.

1. Design normal LVDT with 100 turns in primary and a total 200 turns in each secondary winding with double layer.
2. Give AC supply with 1Amp current to primary winding.
3. Place the iron core across the primary coil in such a way that the voltage induced in the both the secondary's gets cancelled each other and this position is known as 'Null Position'.
4. Now move the iron in forward direction and note the readings of both voltmeters.
5. Similarly repeat the Step 4 in reverse direction.
6. Plot the graph by taking forward displacement along positive X-axis and reverse displacement along negative X-axis and total voltage along Y-axis.
7. Determine the linearity i.e. lower bound point and upper bound point.
8. Now calculate the slope (m) of the linearity and determine the line equation passing through origin having the slope (m) [i.e. y=mx].
9. Now move the iron to any arbitrary position and note the readings of both the voltmeters and the total voltage. Now the following inferences were obtained
 - If the sign of the total voltage is positive indicates forward direction and the value indicates the position (x) of the iron. [i.e. x=y/m]
 - If the sign of the total voltage is negative indicates reverse direction and the value indicates the position (x) of the iron. [i.e. x=y/m]
 - If the value of the total voltage is zero indicates 'Null Position'.
10. The results were validated using graph and with the known values.
11. To increase the accuracy and the reliability of the calculations, a 'C' language program was developed.

The practical view of the developed LVDT is shown in Fig.17.

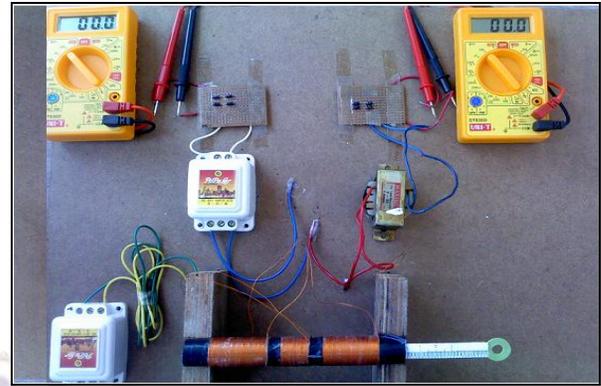


Fig.17. Real time working model of Modified LVDT

G. Conventional LVDT & Modified LVDT Results

The normal LVDT output voltages in both the forward and reverse directions.

Table.1: Voltages in forward/backward directions in normal LVDT

S.No	Forward Distance	V	Reverse Distance	V
1	1	0	0	0
2	2	0.2	0.4	0.2
3	3	0.4	0.8	0.4
4	4	0.6	1.2	0.6
5	5	0.8	1.6	0.8
6	6	1	2	1
7	7	1.2	2.4	1.2
8	8	1.4	2.8	1.4
9	9	1.6	3.2	1.6
10	10	1.8	3.5	1.8
11	11	2	3.7	2
12	12	2.2	3.8	2.2
13	13	2.4	3.8	2.4
14	14	2.6	3.6	2.6
15	15	2.8	3.4	2.8

The graphical representation of the above values shown in Fig.18, there is a linear relationship between the displacement and the voltage induced in the secondary windings.

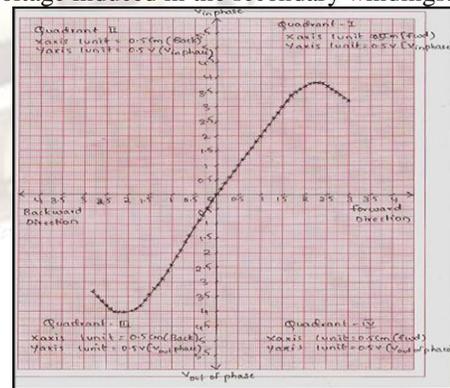


Fig.18. Variation of voltages in Conventional LVDT

The Modified LVDT output voltages with respect to distance and directions are listed in Table.2.

Table.2: Voltages in forward/backward direction for Modified LVDT

S.No	Forward Direction				Reverse Direction			
	X	V ₁	V ₂	V _{Total}	X	V ₁	V ₂	V _{Total}
1	0	2.97	-2.97	0	0	2.97	-2.97	0
2	0.2	3.15	-2.65	0.5	-0.2	2.67	-3.17	-0.5

3	0.4	3.32	-2.32	1.0	-0.4	2.40	-3.4	-1
4	0.6	3.48	-1.98	1.5	-0.6	2.11	-3.61	-1.5
5	0.8	3.64	-1.64	2	-0.8	1.85	-3.85	-2
6	1	3.70	-1.3	2.4	-1	1.60	-4.10	-2.5
7	1.2	3.83	-1.08	2.75	-1.2	1.32	-4.32	-3
8	1.4	3.85	-0.85	3	-1.4	1.04	-4.55	-3.51
9	1.6	3.79	-0.54	3.25	-1.6	0.83	-4.64	-3.81
10	1.8	3.72	-0.37	3.35	-1.8	0.65	-4.77	-4.12
11	2	3.68	-0.27	3.41	-2	0.48	-4.78	-4.30
12	2.2	3.50	-0.25	3.25	-2.2	0.33	-4.79	-4.46
13	2.4	3.32	-0.20	3.12	-2.4	0.22	-4.72	-4.5
14	2.6	3.09	-0.09	2.96	-2.6	0.16	-4.62	-4.46
15	2.8	2.78	-0.07	2.71	-2.8	0.11	-4.48	-4.37
16	3	2.51	-0.05	2.46	-3	0.08	-4.31	-4.23

The graphical representation of the above values shown in Fig. 19, there is a linear relationship between the displacement and the voltage induced in the secondary windings.

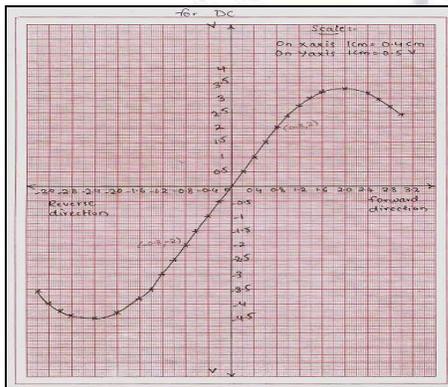


Fig.19. Variation of voltages in Modified LVDT.

Graphs 1 and 2 are very similar and there exists a relation between displacement and the voltage. Direction is given by the sign of the total voltage.

The linearity exists between lower bound point (-1.6,-3.81) and upper bound point (1,2.4) with a tolerance of 0 to ± 0.25mm.

H. Validations

The following table gives the details of validation of the modified LVDT using graph and known values.

Table.3: Validation table for Modified LVDT output voltages

S.No	V ₁	V ₂	V _{Total}	Direction	Displacement*
1	3.27	-2.3	0.97	Forward	0.35
2	3.37	-1.96	1.41	Forward	0.5
3	3.81	-0.7	3.11	Forward	1.52
4	1.48	-4.18	-2.7	Backward	-1.1
5	0.22	-4.73	-4.51	Backward	-2.43
6	0.16	-4.56	-4.40	Backward	-2.8
7	3.5	-0.12	3.38	Forward	2
8	1.71	-3.96	-2.25	Backward	-0.9

*Displacement is with respect to the last position of the iron.

I. Software Implementation

A C-language program was developed to calculate displacement and position of the iron very accurately with speed. The steps to develop C program were given below.

1. Calibration of the program.
2. Calculation of the displacement and position.

In calibration procedure C-program was programmed by using lower and upper bound points and null value voltages.

While in step 2, if you enter the values of the voltmeters (V1, V2) corresponding to displacement, then the program gives the position and displace of the iron from null position. Fig. 21 shows the output screen of the possible cases given in Table.3.

The flow chart representation of algorithm used for the program was given below.

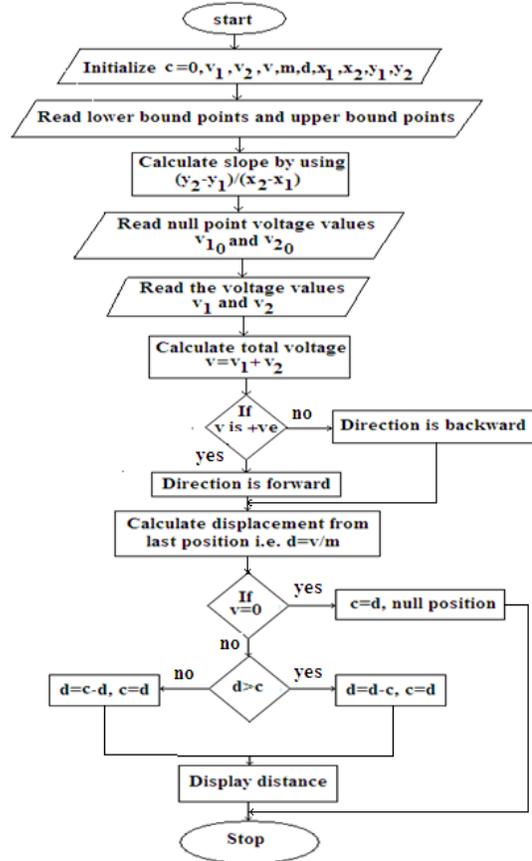


Fig.20. Flow chart for C-program implementation

```

***** WELCOME TO LVDT PROJECT *****
Step 1: Calibration of program
Enter the values for lower bound 'X1,Y1'
-1.6 -3.81
Enter the values for upper bound 'X2,Y2'
1 2.4
SLOPE Value is : 2.388462
Enter null v10&v20 values:
2.97 -2.97
Step 2: Calculation of POSITION & DIRECTION
Enter values for V1 and V2
3.37 -1.96
DIRECTION IS : Forward
DISPLACED DISTANCE FROM LAST POSITION :
0.590338
Step 2: Calculation of POSITION & DIRECTION
Enter values for V1 and V2
0.22 -4.73
DIRECTION IS : Backward
DISPLACED DISTANCE FROM LAST POSITION :
2.478583
    
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Step 2: Calculation of POSITION & DIRECTION
Enter values for V1 and V2
3.5 -0.12
DIRECTION IS          : Forward
DISPLACED DISTANCE FROM LAST POSITION :
3.303382
Step 2: Calculation of POSITION & DIRECTION
Enter values for V1 and V2
1.71 -3.96
DIRECTION IS          : Backward
DISPLACED DISTANCE FROM LAST POSITION :
2.357166

Step 2: Calculation of POSITION & DIRECTION
Enter values for V1 and V2
    
```

Fig.21. C-program output for the various input voltages

J. Limitations

This project has the following limitations.

1. Magnetic saturation of coils was neglected.
2. The losses because of transformers decrease the reliability of the sensor.
3. The losses due to eddy currents and hysteresis were neglected.
4. The materials used in equipment are not magnetically calibrated.

IV. CONCLUSION

Hence, this article confirms that the measurement of position as well as direction of the movable iron of LVDT was possible if the connections of the secondary windings were modified. The FEMM results confirm that the magnetic field distribution from primary coil to secondary coil is uniform. So that the voltage induced in the secondary windings was according to the movement of the iron.

The output results of Modified LVDT displacements were valid and these results were verified using c-program.

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