PAPER

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Construction and remote demonstration of an inexpensive but efficient linear differential variable transformer (LVDT) for physics or electronics teaching during COVID-19 pandemic

Arijit Roy[1], **Durjoy Roy**[2,*] and **Abhishek Mallick**[1]

[1] Department of Electronics, West Bengal State University, Barasat, India
[2] Department of Electronic Science, Rishi Bankim Chandra College, Naihati, India

E-mail: roy.durjoy@gmail.com

Abstract

A linear variable differential transformer is termed as LVDT in short. A simple miniature and inexpensive LVDT was constructed for laboratory teaching. Starting from the fundamental physics of LVDT, a complete demonstration was presented. The heart of an LVDT is three coils that were taken from the electrical 'Ding-dong' doorbell. A universal laboratory experiment kit named 'ExpEyes-17' is used to drive the LVDT and display the input and output signals on a laptop screen. Thus, a compact LVDT system was developed. Displacement experiments were conducted, and the well-known V-shape response for our LVDT was obtained. The theory and experiment were presented with a high degree of clarity for ease of understanding. A complete demonstration was given to a group of students while teaching the theory of LVDT, and an excellent response from the group was obtained. Moreover, online demonstration of LVDT experiments using our kit was easily achievable. The authors have used the setup for

* Author to whom any correspondence should be addressed.

remote demonstration the experiment to the students during COVID-19 pandemic lockdown.

Keywords: construction, demonstration, LVDT, physics teaching, online teaching, ExpEYES-17

1. Introduction

The worldwide outbreak of the COVID-19 pandemic, and the subsequent lockdowns, has called for a paradigm shift in the physics laboratory teaching. Albeit teaching theories could be managed somehow online, the biggest challenge remained the conduct of online laboratory sessions where minimal or absolutely no equipment setup was available for demonstration of laboratory experiments to the students. Teacher's across the length and breadth of the world has searched for ways to teach the laboratory experiments, and many of them, devised indigenous, and sometimes brute & crude methods to demonstrate laboratory experiments to their students. Articles [1–4] are some of such approaches that got recognized by reputed journals that deal with physics education. This article elaborates yet another example of laboratory experiment, developed in home by the authors using basic available components, and demonstrated to the students using popular online meeting platform.

2. Theory

The term LVDT is the short form of linear differential variable transformer or transducer. It is used to measure the static displacement of an object in the range of a few centimeters with a high degree of precision and repeatability. The most popular use of LVDT is as transducers that transform mechanical linear change in position to its electrical equivalent. LVDT is extensively used in manufacturing industry as well, as a metrological tool. As an example, in the manufacturing of turbine blades, various dimensions of a blade are controlled by LVDT. LVDT is taught in various courses, including graduate physics and electronics. The theory of LVDT can be found in standard textbooks [5]. At present, the laboratory trainer kit for demonstrating LVDT is costly. Further, it takes space, and unlikely it could be demonstrated from home or from a laboratory through online mode. On the other hand, we have constructed an inexpensive and miniature LVDT using simple components. Our LVDT was PC compatible (through USB interface) and takes very less space. Not only these, but using our LVDT system, one can demonstrate the LVDT experiments from home through online mode.

2.1. Physics of LVDT

The physics behind the operation of an LVDT is electromagnetic induction. An electromotive force (EMF) is produced in a coil when placed in the proximity of a changing magnetic field (time-varying magnetic field). This phenomenon is known as electromagnetic induction and is best described by Faraday's law of electromagnetic induction. Faraday's law states that an EMF is induced in a conductor when exposed to a changing magnetic field. Mathematically this law is expressed as,

$$E = -\frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{1}$$

where E is the induced EMF and ϕ is magnetic flux. For a tightly wound coil of wire, composed of N number of identical turns and each loop (turn) facing magnetic flux of ϕ, the equation (1) is expressed as

$$E = -N\frac{\mathrm{d}\phi}{\mathrm{d}t}. \tag{2}$$

A current-carrying conductor, on the other hand, produces a magnetic field, and so does the induced current (the term 'induced current' refers to the current produced by the induced EMF when the circuit is closed) around that conductor. We can call this magnetic field an induced magnetic field. Lenz's law of electromagnetic induction states that the direction of the induced current will be such that the induced magnetic field opposes the initial changing magnetic field.

Let us consider a simple example to explore the above phenomenon. Consider a coil A, as shown in figure 1. If the driving power supply is

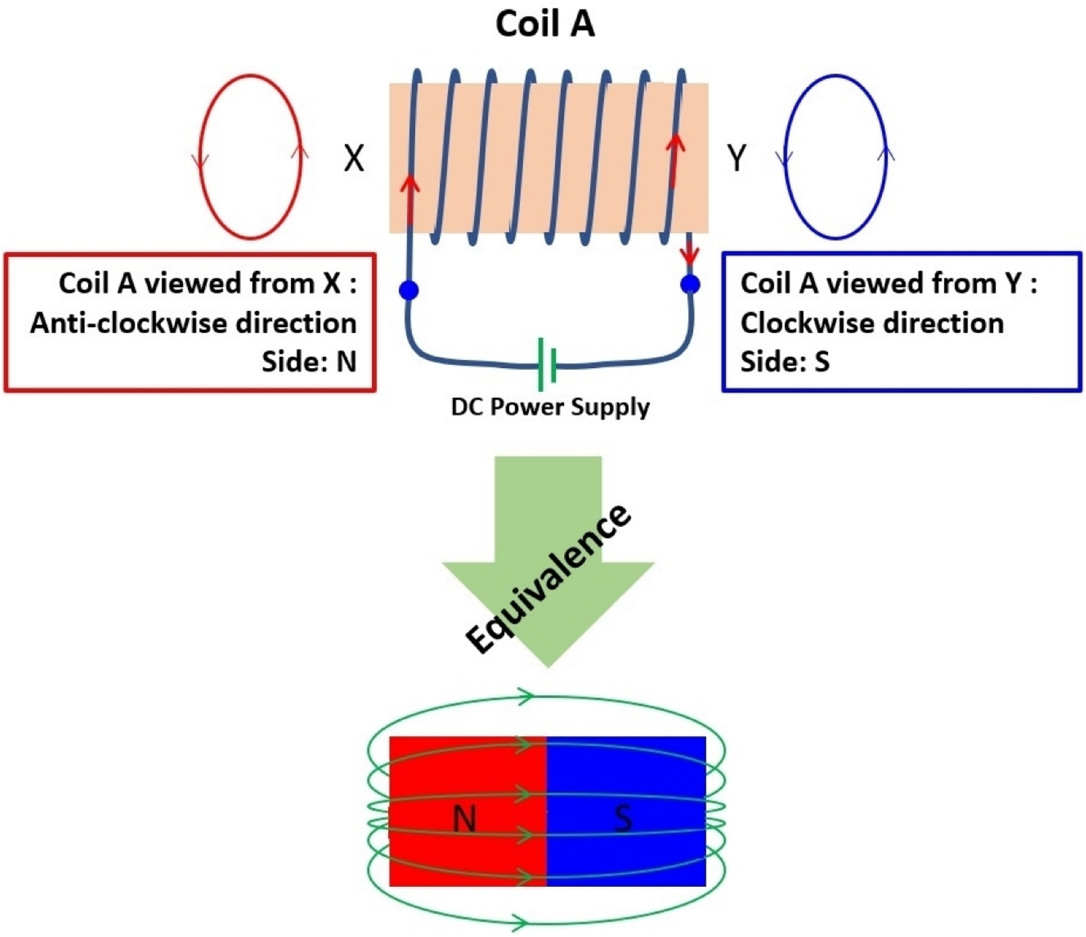

Figure 1. An electromagnet and its equivalence to a permanent magnet.

a fixed DC supply for this coil, then a constant magnetic field (which does not vary with time) is produced around the coil, as shown in the same figure. By changing the direction of the current in the coil (which can be simply done by swapping the supply polarity), we get the same magnetic field but in the opposite direction.

Now, by replacing the DC power supply with a suitable AC power supply $V = V_0 \sin(2\pi ft)$, where V_0 is the amplitude and f is the frequency (of the AC supply), we can produce a changing magnetic field (time-varying magnetic field) around the coil A shown in figure 2. Let us place another coil B near coil A as shown in figure 2. Consider the first quarter cycle of the supply voltage V. In the first quarter cycle, V is positive and increases to V_0 from zero. Let the direction of current in coil A during the first quarter of the cycle of the AC source is as shown in figure 2. The direction of the magnetic field produced by coil A in the first quarter cycle is also shown in figure 2. Since V is increasing, the magnetic flux in coil B is also increasing and hence $\frac{\mathrm{d}\phi}{\mathrm{d}t}$ is a positive quantity. According to Lenz's law, the direction of the induced magnetic field in coil B would be such that the magnetic field produced by coil A and the induced magnetic field around coil B should repel each other. Thus, the direction of the induced magnetic field is obtained. From the direction of the induced magnetic field, the direction of current in coil B is determined and is shown in figure 2. For the circuit configuration shown in figure 2, the AC supply waveform in coil A, and the induced EMF in coil B, are shown at the bottom of figure 2.

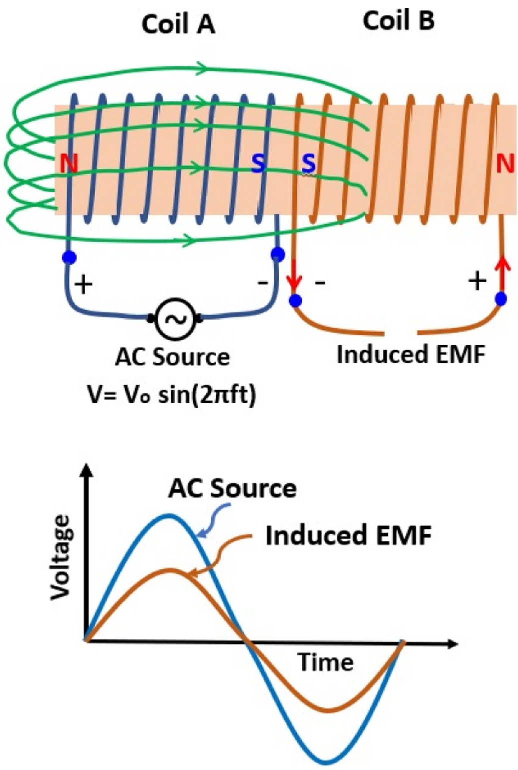

Figure 2. Pictorial description of Faraday's law of induction.

If coil B is wound in the opposite direction, then the supply voltage and induced EMF will be out of phase.

The induced EMF can be significantly increased by using a magnetic material as the core material in the coils. A magnetic material (iron, nickel, cobalt, steel, and their compounds) quickly gets magnetized by applying a magnetic field to it. The magnetic permeability of the material quantifies this ability. For example, the magnetic permeability is about 5000 times the free space permeability for 98% pure iron. The magnetic permeability of steel is about 100 times the permeability of free space. Thus, by using an iron core, the efficiency of coil A or coil B can be increased significantly. When the iron core is used for coil A (see figure 2), its magnetic flux production ability rises significantly. When the same is used in coil B, its ability to produce induced EMF increases significantly.

Another factor that greatly affects the magnetic permeability of a material is the frequency of operation. The magnetic permeability (more specifically, AC permeability) is strongly dependent on frequency, and at higher frequencies, the permeability decreases significantly for iron, steel etc [6, 7]. Therefore, at higher frequencies (more than 1.5 kHz), the induced EMF is reduced. If possible, the frequency sensitivity of the core material on the induced EMF is to be tested. The frequency at which the induced EMF is highest, that frequency should be used as the operating frequency of the LVDT.

2.2. Basic principle of LVDT

LVDT is a passive transducer that measures displacement. It consists of a primary coil wound on a hollow cylindrical rod (non-conducting) and is driven by an ac source (input). It also consists of two secondary coils having an equal number of turns and wound on the same cylindrical rod at an equal distance from either side of the primary coil, as shown in figure 3. The two secondary coils are connected in a series-opposition configuration. This means that if the current flows in clockwise direction in one of the secondary coils, then the current will flow in an anti-clockwise direction in the other secondary coil and vice versa. This series opposition connection confirms that the resultant EMF in the secondary coils is $E_0 = E_{S_1} - E_{S_2}$, where E_{S_1} and E_{S_2} are the EMF induced in the first S_1 and second S_2 secondary coils respectively. A movable iron core is placed inside the hollow cylinder. The position of this iron core with respect to the two secondary coils will affect the magnetic coupling between the primary and two secondary coils.

Let us describe how the LVDT works. At very first, the primary coil is excited by a source (input), and as a result, alternating current starts flowing into the primary coil and which in turn produces varying magnetic fields near the primary coil. This varying magnetic field interacts with the two secondary coils, and alternating EMF is induced in the secondary coils. Initially, let us assume the iron core is placed in the center, or in other words, it is placed in the middle of the primary coil. In this situation, equal EMFs are

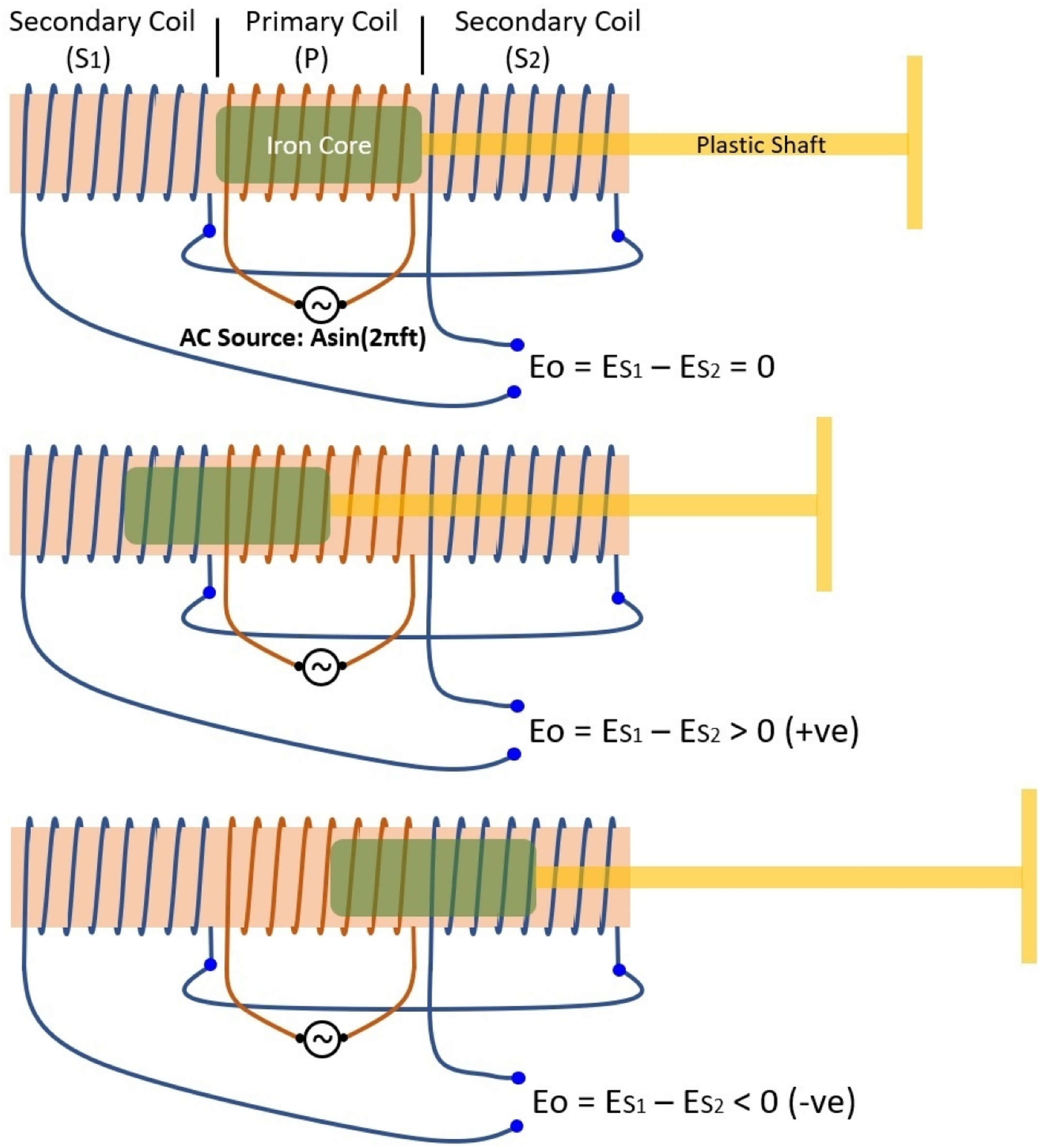

Figure 3. Schematic description of working principle of an LVDT.

induced into the two secondary coils. As a result, the resultant EMF becomes zero (due to the series opposition configuration). This situation is shown at the top of figure 3. This position of the core is known as the 'Null' position.

When the iron core is placed toward the left, then the amplitude of the induced EMF in the secondary coil S_1 is more than that of in S_2. Hence, output is dominated by EMF induced in S_1. It is possible to find a position of the iron core for which amplitude E_0 is maximum. This situation is shown in the middle of figure 3. Upon further increase in displacement of the iron core towards the left, the output is decreased. This is because, the iron core shared by the primary coil and secondary coil S_1 is not optimum for this position of the core. When the iron core is placed towards the right with respect to the Null position, the EMF

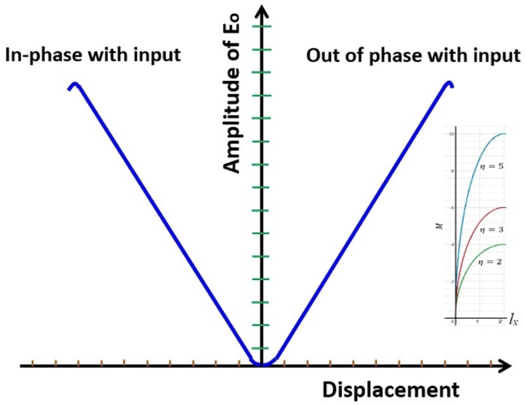

Figure 4. Typical output of an LVDT as a function of displacement. The inset figure shows the variation of M (mutual inductance) as a function of l_x (displacement) (5).

induced in S_2 is more than that of in S_1, and as a result, the output is dominated by the secondary coil S_2. The situation is shown at the bottom of figure 3. It is to be noted here that with respect to the input, the output is in the phase for S_1 (or S_2) dominated output and out of phase for S_2 (or S_1) dominated output. Thus, the variation of the amplitude of the output EMF as a function of displacement would be a V-shape graph similar to what is shown in figure 4.

In figure 4, at the both sides of the 'Null' position, the amplitude of the induced EMF is approximately linear up to a certain amount of displacement. Let us try to understand why such relationship is linear. The amplitude of the induced EMF is dependent on the mutual inductance between the coils. The linear relationship can be explained from the linear variation of mutual inductance between the coils as a function of displacement of the core. It is to be noted here that the mutual inductance is derived using Faraday's law of induction.

Let us assume the number of turns per unit length is constant (n) for all the coils and we have a cylindrical hollow space (length of which is about the three times the length a coil) for the core as shown in figure 3. Now in figure 3, consider a position of the iron core such that it consists of N_{S_1} number of turns of the S_1 and N_P number of turns of the coil P along the length of the iron core. Further, consider at this position of the core, l_x and l_p are lengths of the iron core in the coil S_1 and P respectively. Ignoring the air-core portions of the coils, the mutual inductance between the coils is [8],

$$M \propto \frac{N_{S_1} N_P}{\sqrt{l_x l_p}}. \tag{3}$$

In terms of n, the above expression can be written as

$$M = k\frac{n^2 l_x l_p}{\sqrt{l_x l_p}} = \eta\left(\sqrt{l_x l_p}\right) \tag{4}$$

where k is a constant.

Assuming L_c is the length of the iron core, we can rewrite the above equation as follows

$$M = \eta\sqrt{l_x(L_c - l_x)} \tag{5}$$

where, $\eta = kn^2$ is another constant.

Assuming L_c to be 4 cm, the variation of M as a function of l_x (displacement) is shown as an inset of the figure 4 where a linear variation can be observed.

The degree of linearity is highly dependent on the constant η.

3. Experiment

3.1. Construction of the LVDT

The LVDT is constructed using commonly available low-price components. The components were then assembled to construct the LVDT, as shown in figure 5. Most of the components were scavenged from discarded common household articles. However, the authors are specifying the approximate cost to construct such an experimental setup; the prices are converted to Euro (€) from Indian Rupees (₹) for easy understanding of the readers. The components used to develop the LVDT, their sources, and approximate costs are listed in table 1. The complete setup costed less than €4.

Three coils were taken out from three Ding-Dong doorbells (commercial household electrical doorbell that operates at 220 V, AC 50 to 60 Hz). These coils were made by winding 27 standard wire gauge, (about 0.4166 mm in diameter) copper wires on a plastic spool. One iron core from a

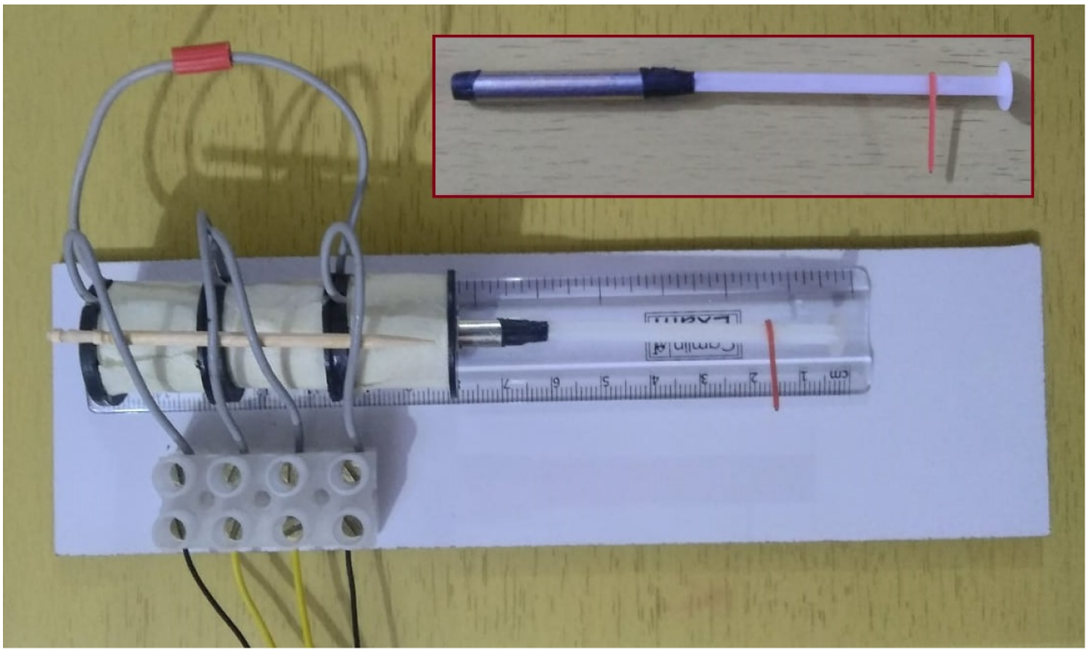

Figure 5. LVDT constructed by the authors.

Table 1. Components used to construct the LVDT.

Components	Description	Approx. cost
Coil (3 pcs)	Coils were taken from the solenoids of the common household ding-dong door bells. Resistance of each solenoid was about 430 Ω.	€3.30
Base board (1 pc)	Wooden board commonly used for Electrical Switch Board	€0.15
Plastic Ruler (1 pc)	15 cm Ruler. Plastic ruler was used to avoid any EMI on the experiment setup	€0.05
Plastic shaft (1 pc)	This was taken from disposal syringe used for insulin injection	€0.10
Terminal Connector (1 pc)	4-point Terminal Connector, commonly used for electrical connection	€0.15
Miscellaneous	Fevikwik (Adhesive) 1 tube (small), 1 pc Plastic Straw.	€0.10

doorbell was also taken out. The plastic shaft for the core was made from the plunger of a disposable syringe (10 ml, usually used to inject insulin). The rubber pad from the syringe's plunger was removed, and the end surface of the plunger was polished, and then the iron core was attached at that end of the plunger using the strong adhesive. In this way, the iron-core-plastic shaft was made (see inset of figure 5). Next, the adhesive was applied to the external surface of a straw. The straw was then inserted through the center hole of the coils, and they were arranged as close as possible to each other, and the extra straw was cut down. It was made sure that the plastic shaft with the iron core can move freely through the cylindrical straw. The plastic ruler was then fixed onto the wooden base board using the adhesive. At one side of the ruler, the coil assembly was fixed using the adhesive. A piece of red colored wire about 2 cm long was then fixed into a plastic shaft to indicate the position of the core on the ruler. Then, a dummy experiment was conducted to obtain the correct terminal to be connected together for the secondary coils. This was done by looking at the phase reversal of the output signal with respect to the input signal while moving the shaft from left to right or right to left. After confirming the phase reversal, the secondary coils were connected in series. Next, a 4-point terminal connector was fixed on the board using the adhesive, as shown in figure 5. The primary coil was then connected to the two middle terminals, while the secondary coils were connected at the two extreme terminals, as shown in figure 3. The input was to be applied at the end of the two middle terminals, while the output was to be taken from the two extreme end terminals.

3.2. The platform of the experiment: ExpEYES-17

The platform of the experiment was the ExpEYES-17 kit, designed under their Phoenix Project by the University Grants Commission (UGC, the apex government body of Indian higher education ecosystem) establishment IUAC [9], New Delhi, India. The kit is built around a PIC24EP256GP204-I/PT micro-controller. It interfaces with a computer, running Linux or Windows through a USB 2.0 serial connection, and is driven by the power drawn from the computer itself; no external power supply is required. It has three Input/Output blocks, out of which, two were used in this experiment. I/O lines were available to the users via 16 pin spring loaded terminal blocks. The kit can generate different signals like variable DC and AC voltages (± 5 V DC, ± 3.3 V DC, ± 5 V AC, of shapes like sinusoid, triangular and square, digital output etc), and on the other hand, it has four oscilloscope channels built in (A_1, A_2, A_3 & MIC) of different sensitivities. In this experiment, the authors have used only the signal generator and oscilloscope part of the device, and complete description of the device is

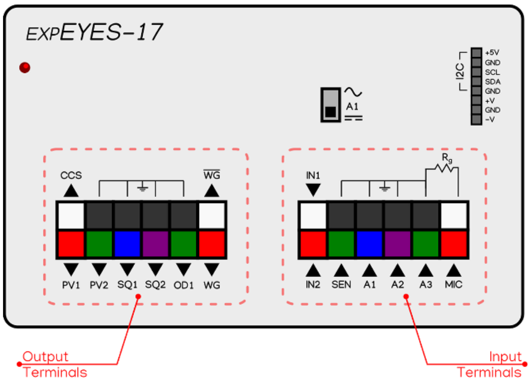

Figure 6. The schematic of ExpEYES-17 kit [14]. The terminal blocks at the left are the output signals, and those at right are the input channels. We have used channels A_1 and A_2 in this experiment as DSO inputs, and WG (waveform generator) as input to the LVDT.

out of the scope of this article. However, Roy [1] may please be consulted for detail description of the device. The user manual of ExpEYES-17 [10] can be downloaded from their repository. Detailed device description including circuit schematics can also be obtained from their website [11]. The most interesting feature of the devices is that the software and hardware of the device is completely open source, and published under GNU-GPL [12] & CERN-OHL [13] licences, respectively. The figure 6 shows the schematic of the user interface of the device, and the figure 7 shows the software interface during this experiment on Windows.

3.3. Setting up the experiment and procedure

The experimental setup consists of three systems, namely

(a) the constructed LVDT,
(b) a universal trainer kit named 'ExpEyes-17' and
(c) a laptop (or PC).

The brief details of the 'Your Lab@Home' trainer kit ExpEyes-17 is given in the section 3.2. The price of this universal trainer kit is about €50 only. In this experiment, the role of ExpEyes-17 trainer kit was of two folds. First, it provides an

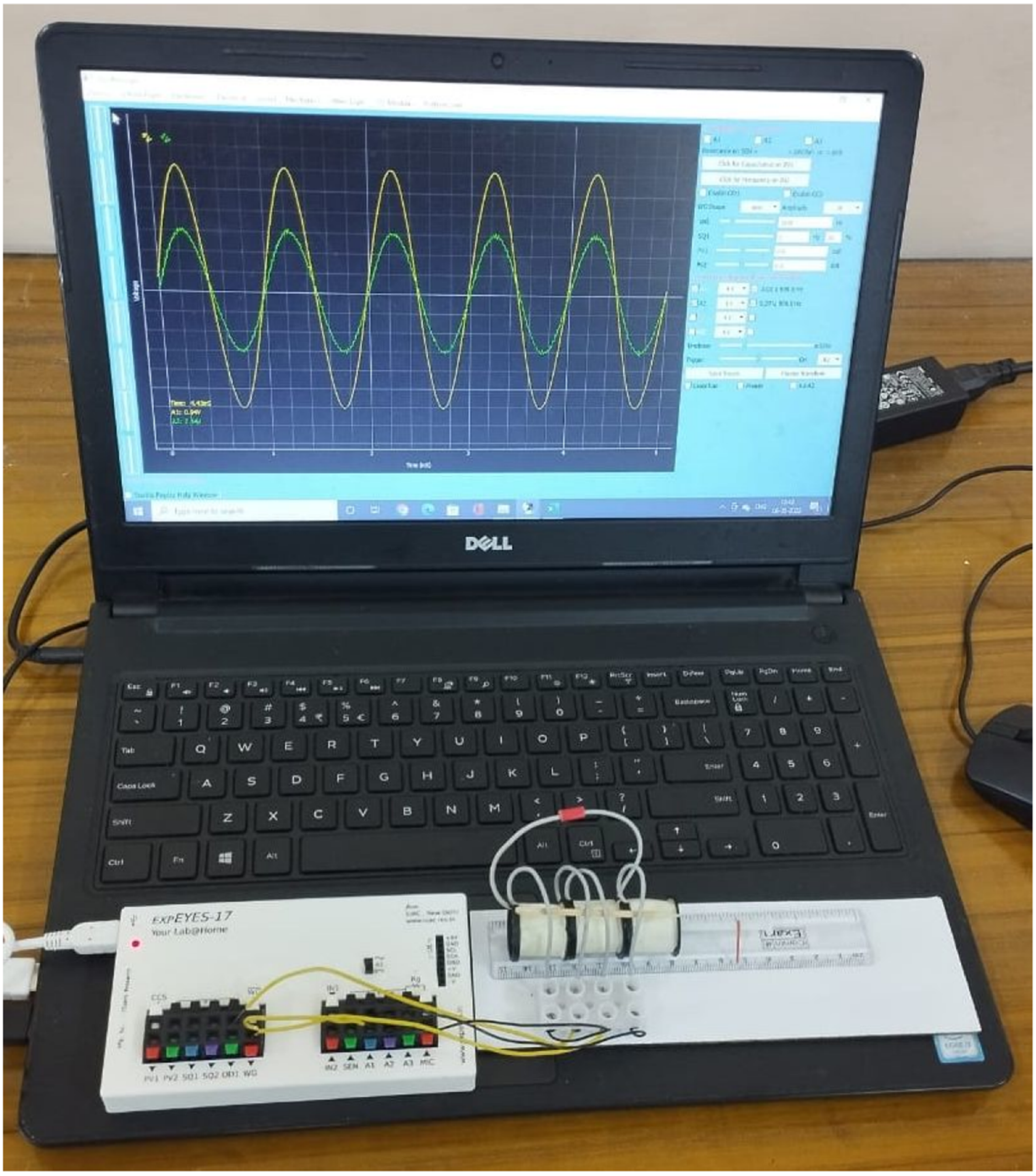

Figure 7. Experimental setup for studying LVDT. The complete system is powered by the USB 2.0 interface of the laptop.

AC power supply for the primary coil. Secondly, it provides the display of AC signals on the computer screen. That is, it provides Digital Storage Oscilloscope/ Cathode Ray Oscilloscope (DSO/CRO) capability on the computer screen. The kit is connected to the computer through a USB interfacing cable. The free downloadable software for the kit provides all necessary controls through its user interface. A photograph of the entire setup is shown in figure 7.

As mentioned earlier, the induced EMF can be significantly increased by placing magnetic material inside the coil. This fact was verified quantitatively before the actual experiment of

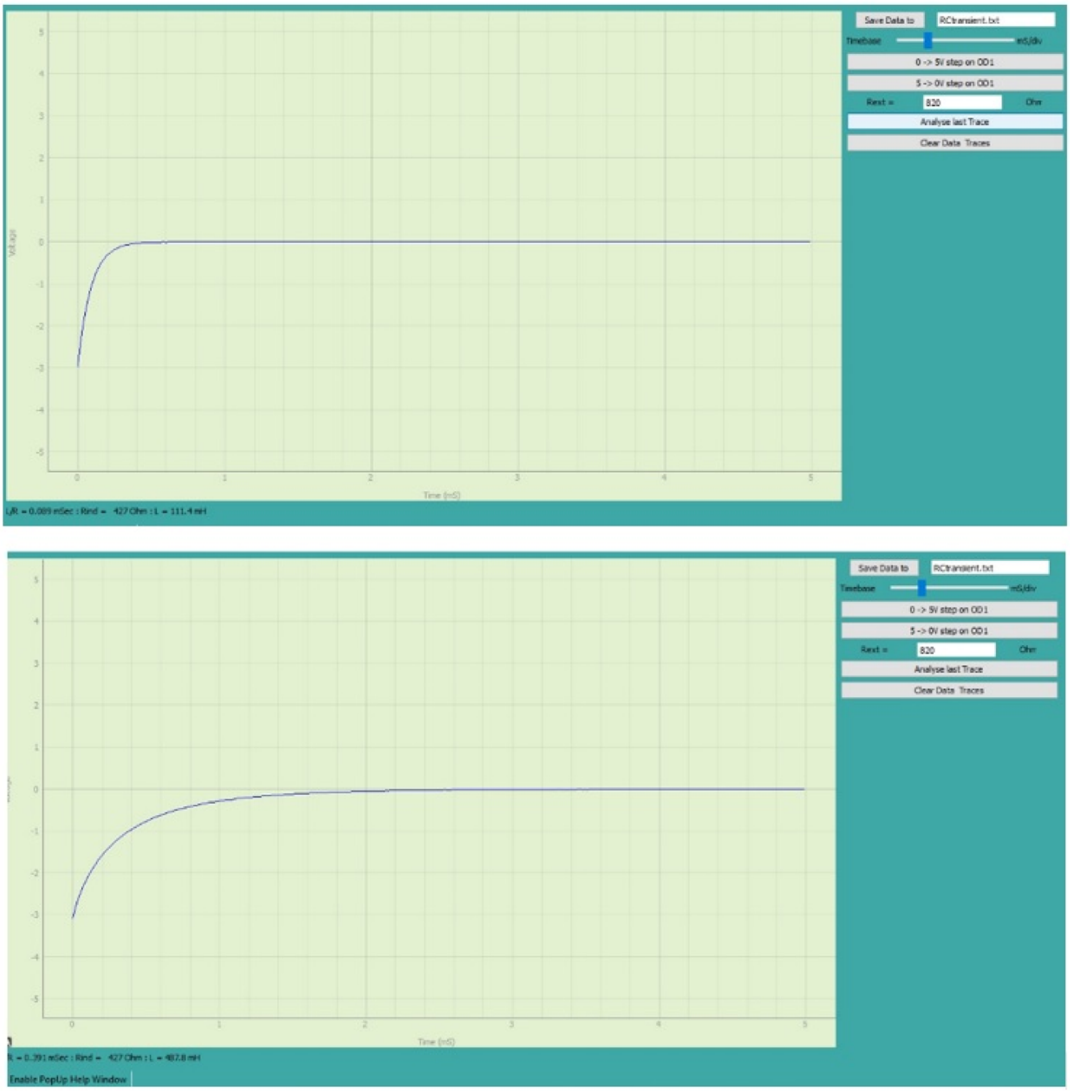

Figure 8. Measurement results of inductance without core (top) and with core (bottom). Results in terms of numerical values are displayed at the bottom of each screenshot.

LVDT. Using the ExpEyes-17 kit, it is possible to measure the unknown inductance *L* of a coil. Basically, the kit does a transient analysis for an *LR* circuit (in which, *L* was unknown, and externally connected *R* was known). Then by fitting the transient response, the time constant of the *LR* circuit is calculated. Since, the value of the resistance connected in the *L*–*R* circuit was given as input, the software computed *L* and displayed its value on the screen. We have used a resistor of 820 Ω as the known resistance and connected to the kit for the *LR* circuit. The inductance *L* of a coil was then measured without and with a steel core. The measurement results are shown in figure 8. The measured inductance without and with the core was 111.4 mH and 487.8 mH respectively. Notice that the inductance was increased by a factor of 4.4 due to the presence of the core. The software also displays the internal resistance of the coil, which was 427 Ω. In this way, the electrical properties of coils were obtained. Measuring the electrical properties of the coil was not mandatory for

Table 2. LVDT response data.

Disp. (cm)[a]	Output: amplitude of E_0 (V) $f = 0.5$ KHz	$f = 1.0$ KHz	$f = 1.5$ KHz	Side w.r.t.[b] 'Null' position
2.6	0.7	0.73	0.69	
2.7	0.73	0.76	0.71	
2.8	0.75	0.77	0.72	
2.9	0.76	0.77	0.71	
3.0	0.76	0.76	0.7	
3.1	0.74	0.73	0.67	
3.2	0.72	0.7	0.65	
3.3	0.68	0.66	0.62	
3.4	0.65	0.63	0.58	
3.5	0.6	0.58	0.53	
3.6	0.55	0.55	0.49	RIGHT
3.7	0.51	0.5	0.45	
3.8	0.46	0.44	0.41	
3.9	0.41	0.39	0.36	
4.0	0.35	0.34	0.31	
4.1	0.29	0.29	0.26	
4.2	0.23	0.23	0.21	
4.3	0.18	0.18	0.16	
4.4	0.12	0.13	0.12	
4.5	0.05	0.06	0.05	
4.6	0.01	0.01	0.00	NULL
4.7	0.05	0.06	0.05	
4.8	0.12	0.13	0.12	
4.9	0.18	0.18	0.16	
5.0	0.23	0.23	0.21	
5.1	0.29	0.29	0.26	
5.2	0.35	0.34	0.31	
5.3	0.41	0.39	0.36	
5.4	0.46	0.44	0.41	
5.5	0.51	0.5	0.45	
5.6	0.55	0.55	0.49	
5.7	0.6	0.58	0.53	LEFT
5.8	0.65	0.63	0.58	
5.9	0.68	0.66	0.62	
6.0	0.72	0.7	0.65	
6.1	0.74	0.73	0.67	
6.2	0.76	0.76	0.7	
6.3	0.76	0.77	0.71	
6.4	0.75	0.77	0.72	
6.5	0.73	0.76	0.71	
6.6	0.7	0.73	0.69	

[a] Displacement of the core along the scale.
[b] With reference to.

LVDT experiment. We presented these measurements for the sake of clarity and specifying the coils for reproducing the LVDT construction in any other laboratory.

Next, after clearing all the traces, the fresh experiment was conducted to study the LVDT. Through the software, the 'Oscilloscope' mode was enabled. An AC signal was applied to the

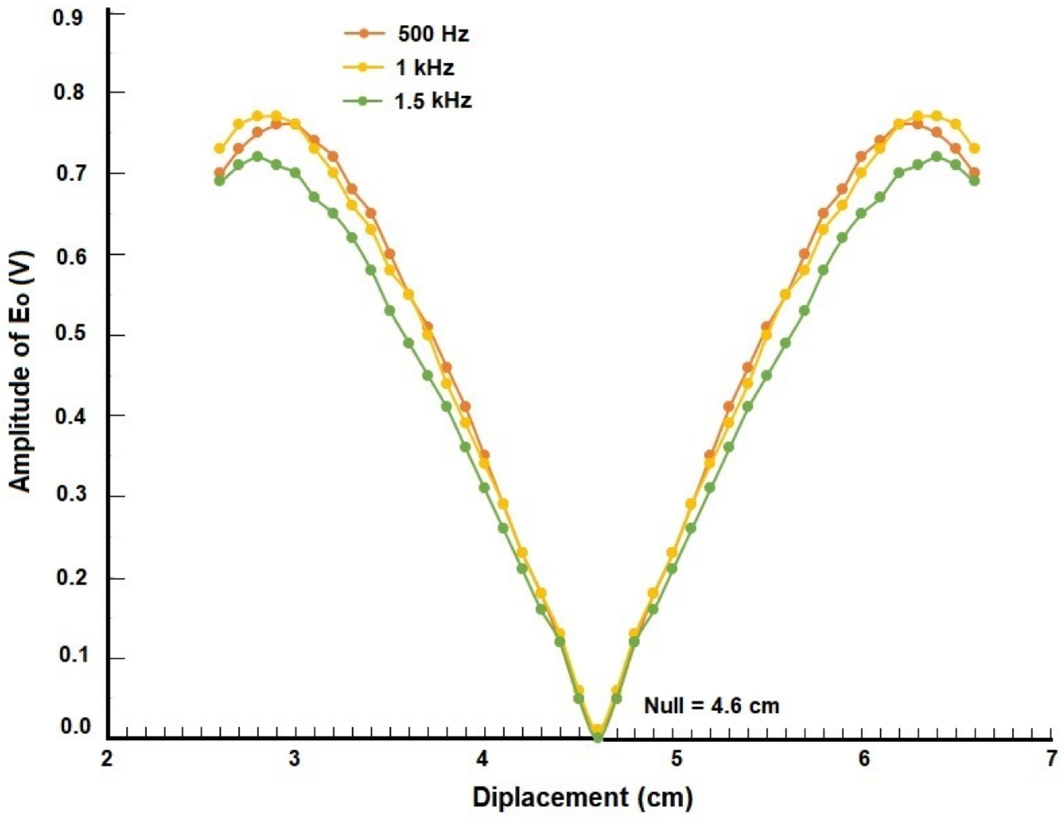

Figure 9. LVDT responses.

primary coil using the kit. The shape, amplitude and frequency of the AC signal were set to 'sine', 3 V and 1000 Hz, respectively through the user interface of the software under 'Oscilloscope' mode. To observe AC signals, input and output signals were respectively taken into the A_1 and the A_2 channels of the kit. Apart from displaying waveforms, the software was able to display the amplitude and frequency of AC signals on the same screen, and we enable this button for both input and output channels.

Albeit the LVDT was made of coils scavenged from Ding Dong Bells that operate in 220 V AC, In this experiment, we operated the set-up with 3 V AC only. The whole experiment setup was powered by a USB 2.0 port of a Laptop, and, the maximum voltage at any open terminal of the whole experiment setup was 5 V, rendering the experiment extremely safe for the students to work with in terms of probability of getting electrical shock.

After setting up the experiment, readings i.e. amplitude of the output signal for the different position of the core were taken in the following manner.

Step 1. The shaft was inserted so that the core was placed in the middle of the primary coil. The position of the core was fine-tuned to get 'zero amplitude' at the output signal. This position of the core was recorded by the ruler and it was nothing but 'Null' position of the core. If exact 'zero' was not possible, then it would be possible to place the core to get output close to zero which was 0.01 V in our present experiment.

Step 2. From the 'Null' position, the shaft was pushed towards the left in steps of about 1 mm and output readings were taken. We continue this process until the reading started to decrease.

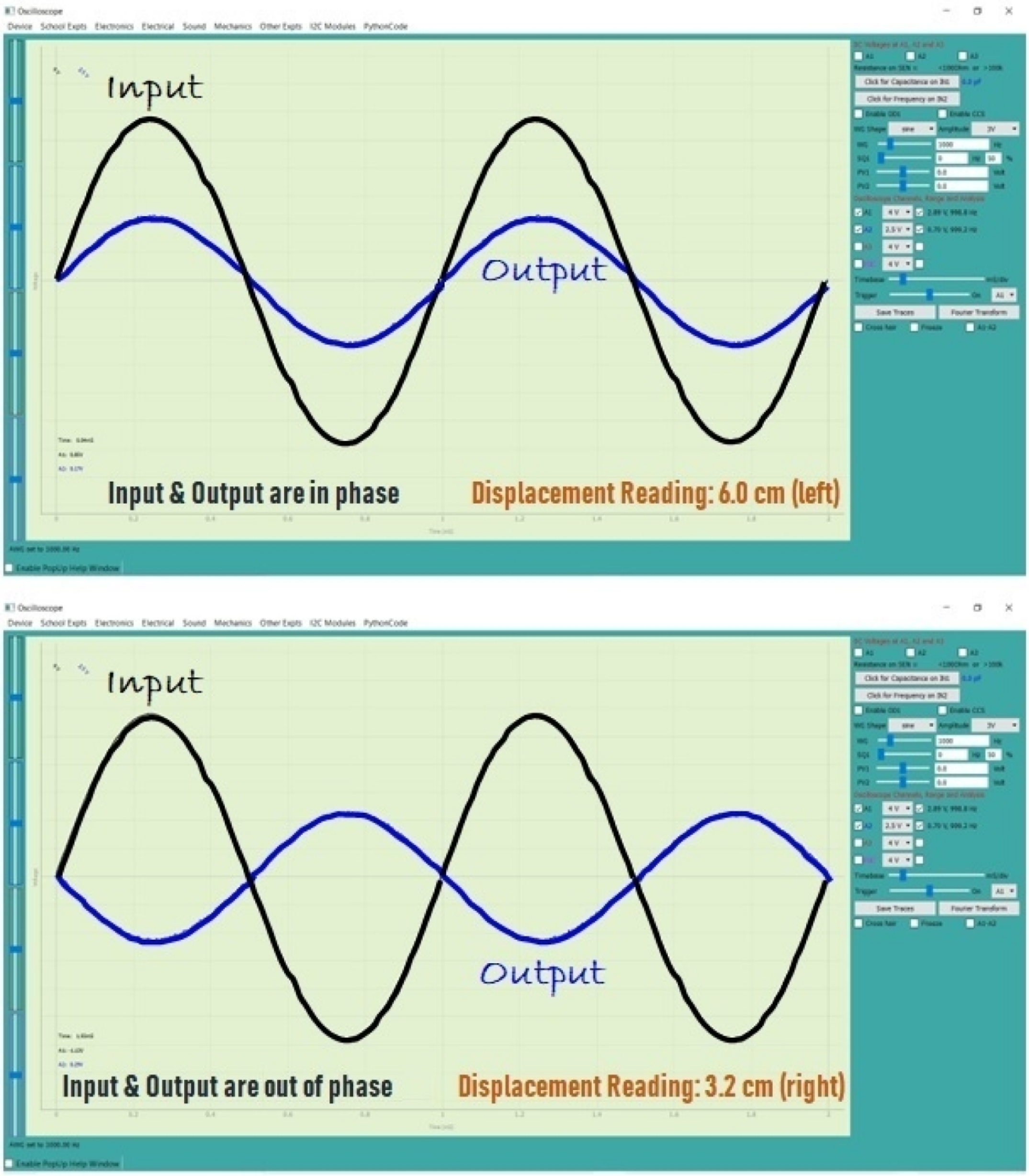

Figure 10. Typical waveforms obtained during measurement. The top figure was captured when the displacement reading was 6.0 cm and core position was on the left side of 'Null' position while the bottom figure was captured when displacement was 3.2 cm and core position was on the right side of the 'Null' position. In top figure, the input and output are in phase while same was out of phase as seen in the figure at bottom.

Step 3. The core was then bought back at the 'Null' position. Then, the shaft was pulled toward the right in steps of about 1 mm and corresponding readings were taken. We continue this process until the reading started to decrease.

Step 4. We repeated steps 2 and 3 five times and average readings were computed.

Step 5. Steps 2–4 were repeated for the other two frequencies (500 Hz and 1500 Hz) of the AC supply to the primary coil.

4. Results and discussion

The output readings (amplitude of the output signal) were tabulated in table 2. When these readings were plotted, V-shaped graph as per expectation was obtained and was shown in figure 9. The 'Null' position of the constructed LVDT was at 4.6 cm. Nonlinearity in LVDT response was expected near the 'Null' position and for displacements near its upper range and such nonlinearity was found in our experiment too (see figure 9). In our experiment, a linear response on either side of the 'Null' position for the displacement of about 1 cm from 0.25 cm away from the 'Null' position was obtained (for an input frequency of 1 kHz). The sensitivity of the LVDT in the linear zone was found to be about 60 mV mm^{-1}.

The phase reversal on either side of the 'Null' position was clearly obtained. Typical snap shot of the signals are shown in figure 10. From the figure 10, it can be observed that the input and output signals were in phase when displacement was on the left side of the 'Null' position while they were out of phase when the displacement was on the right side of the 'Null' position.

The repeatability of the displacement measurement was found to be extremely good in 1 mm resolution. The hysteresis effect was not observed in displacement measurement. We believe that it was possible to achieve sub millimeter resolution in displacement measurements using our LVDT. In order to achieve such a high resolution, a micrometer (screw gauge) or vernier calliper can be attached appropriately with the plunger.

Further betterment of the instrument was possible by optimizing various design aspects of the instrument. For example, instead of steel as the core, the use of iron as the core will definitely increase the induced EMF greatly. Optimization of size, shape, number of turns of the coils, and frequency of operation will provide better sensitivity and resolution.

5. Conclusion

The construction of an inexpensive but efficient LVDT was described. The operation of the developed LVDT was demonstrated clearly with all relevant experimental results. The theory and physics behind the principle of operation of LVDT were also provided at the beginning of this paper. Finally, a complete laboratory demonstration was conducted online to groups of students of Undergraduate and Postgraduate level during lockdown, and an excellent response from the group was obtained. In fact, the students actively participated by recording data and plotting curves.

Writing easy python scripts can enable the student to have a complete control over the experiment remotely, as they can displace the LVDT shaft, in our case, the piston shaft of a syringe, using a stepper motor and linear gear assembly. The main objective of the experiment was not to replace the laboratory experiment set-up, but to augment it, by learning how to design and conduct low cost experiment set-ups and interfacing computer with the experiments to log the data automatically.

The authors are of the opinion that remote conduction of a laboratory experiment, and computer interfaced physics practical's will fetch much more importance in the changed academic environment of post-pandemic era. The experiment described in this article may remain as one of the numerous efforts put on by the Physics teachers across the globe.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Arijit Roy https://orcid.org/0000-0002-9618-6641
Durjoy Roy https://orcid.org/0000-0002-8195-2382
Abhishek Mallick https://orcid.org/0000-0003-2955-7091

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Dr Arijit Roy has attended many prestigious institutes in his career. He received M.Sc. (Physics)degree from Indian Institute of Technology, Kharagpur and M.Tech. (Instrument Technology) degree from Indian Institute of Technology, Delhi in 1999 and 2001 respectively. Dr Roy earned a Ph.D. degree (Electronics) from Nanyang Technological University, Singapore in 2008. He is experienced in industrial as well as academic 'R&D'. Recently he co-authored a textbook 'An Indian Adaptation of Physics book by Robert Resnick, David Halliday, Kenneth S Krane, ISBN: 978-93-5464-038-4', a highly credible and scholarly contribution. His areas of research are Bioimpedance, Instrumentation, Microelectronic Reliability, Quantum Computing. He has delivered more than six seminars as an invited speaker in academic events of repute. Presently, Dr Roy serves as assistant professor in the department of electronics at West Bengal State University where he is driving for excellence in teaching and research.

Durjoy Roy has received his Under-Graduate & Post-Graduate Degrees in Electronic Science from the University of Calcutta. He has been working as an Assistant Professor in Rishi Bankim Chandra College, Naihati since 2010. He has a very keen interest in design & development of low-cost laboratory experiments. His research interest includes the fields of Microcontroller based experiments, Microwaves and Antenna etc.

Abhishek Mallick received B.Sc. (Electronics) and M.Sc. (Electronics) degrees with First Class First position in 2014 and 2016 respectively under the West Bengal State University. Mr. Mallick was awarded the DST Inspire Fellowship scheme from The Department of Science and Technology. His areas of research are Energy Harvesting Circuits, Bioimpedance. He is currently pursuing a Ph.D. and as a teaching assistant in the department of electronics at West Bengal State University.