







## Implementation of an LVDT sensor to measure the viscoelastic deformation of parts created with additive manufacturing


## Implementación de un sensor LVDT para medir la deformación viscoelástica de piezas fabricadas con manufactura aditiva

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









### Abstract










Additive manufacturing has experienced rapid growth due to significantly reduced manufacturing times. Besides, it is versatility, and its costs are low, among other aspects. Fused Deposition Modeling [FDM] is widely used in various sectors including healthcare, construction and aerospace. The most used materials are polymers. These exhibit viscoelastic behavior. In the present work, an LVDT [Linear Variable Differential Transformer] sensor was implemented to measure the viscoelastic deformation of parts manufactured with additive manufacturing. For this purpose, an electronic circuit with its hardware was developed. The LVDT sensor was characterized and calibrated, an interface was developed, and finally, a functional test was carried out. The minimum measurement that the system can perform is hundreds of a millimeter. A comparison was made between the LVDT readings and a dial indicator. The maximum difference between the readings was 0.46 %. The graphical interface allows viewing and saving the readings generated during the tests.

### Resumen

La manufactura aditiva ha tenido un rápido crecimiento debido a que permite reducir significativamente los tiempos de fabricación. Además, es versátil y de bajo costo, entre otros aspectos. El proceso más utilizado es el Modelado por Deposición Fundida [FDM, por sus siglas en inglés]. Se usa en sectores como salud, construcción e industria aeroespacial. Los materiales más utilizados son polímeros. Estos presentan un comportamiento viscoelástico. En el presente trabajo, se implementó un sensor LVDT [Transformador Diferencial de Variación Lineal, por sus siglas en inglés] para medir la deformación viscoelástica de piezas fabricadas con manufactura aditiva. Para este fin se desarrolló un circuito electrónico, se creó un hardware, se caracterizó y calibró el sensor LVDT, se desarrolló una interfaz y finalmente se hizo una prueba de funcionamiento. El sistema permite medir centésimas de milímetro. Se realizó una comparación entre las lecturas del LVDT y un comparador de carátula. La diferencia máxima entre las lecturas fue de 0.46 %. La interfaz gráfica permite visualizar y guardar las lecturas generadas durante las pruebas.

Implementation of an LVDT sensor to measure the viscoelastic deformation of parts created with additive manufacturing		
Objectives	Methodology	Contribution
 Development of an LVDT sensor hardware to measure displacement.	 Electronic circuit development and construction.	 A methodology to implement an LVDT in the measurement of viscoelastic strain is presented.
 Performance characterization of the LVDT sensor.	 Measurement characterization by comparison with a precision instrument.	 An equation is obtained for the evaluation of the performance of the LVDT sensor.
 Development of an interface to visualize reading and log the data.	 Development of a Python Interface.	 Real-time measurement display and data logging.

### Interface, Conditioning, FDM

Implementación de un sensor LVDT para medir la deformación viscoelástica de piezas fabricadas con manufactura aditiva		
Objetivos	Metodología	Contribución
 Crear hardware para sensor LVDT para medir desplazamiento.	 Desarrollo de circuito electrónico y construcción.	 Se presenta una metodología para implementar un LVDT en la medición de deformación viscoelástica.
 Caracterizar el comportamiento del sensor LVDT.	 Caracterización por medio de comparación de un instrumento de precisión.	 Se obtiene una ecuación para el comportamiento del sensor LVDT.
 Desarrollar interfaz para visualizar las lecturas y registrar los datos.	 Desarrollo de una Interfaz en Python.	 Visualización de las mediciones en tiempo real y permite registrar los datos.

### Interfaz, Acondicionamiento, FDM

**Area:** Development of strategic leading-edge technologies and open innovation for social transformation

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## 1. Introduction

In recent years, additive manufacturing [AM], and particularly fused deposition modelling [FDM] technology, has experienced rapid growth due to its potential to transform traditional production processes.

According to Mohsen Attaran [Attaran, 2017], this production process allows for the large-scale manufacture of customised parts, while significantly reducing manufacturing times and accelerating time to market. For their part, Cano et al. [Cano-Vicent et al., 2021] highlight the versatility, low cost and ease of operation of the FDM printing technique and its adoption in strategic sectors such as healthcare, construction and aerospace. In particular, they mention that during the Coronavirus pandemic, this technique was extremely helpful in the manufacture of masks, ventilators, respirators, and nasopharyngeal swabs.

On the other hand, various studies have shown that printing parameters directly influence the mechanical properties of the parts. Gao et al. [Gao et al., 2022] present a summary, based on several articles, of the variables that affect mechanical properties, as well as dimensional properties, such as filament direction, layer thickness, fill density, nozzle temperature, printing speed, etc. This highlights the importance of being able to measure the mechanical behaviour of parts manufactured using AM.

One of the key components for achieving accurate measurement of minimal linear displacements is the Linear Variable Differential Transformer [LVDT].

As Nyce [Nyce, 2003] states, an LVDT is a non-contact position transducer that operates by means of an alternating excitation signal applied to a primary coil, which induces voltages in two secondary coils depending on the position of a moving core. The design and implementation of signal conditioning is one of the main challenges when integrating LVDT sensors into measurement systems.

The literature shows various technical approaches to overcoming the limitations associated with LVDT signal conditioning.

According to Rerkratn [Rerkratn et al., 2020], an effective strategy is to use an RMS-to-DC converter together with an XOR-type phase detector, which allows a continuous output proportional to displacement and direction to be obtained without requiring low-pass filters.

In addition, he proposes a technique based on the hyperbolic sine function to compensate for non-linearity and extend the useful range of the sensor without increasing energy consumption [Rerkratn et al., 2022]. Petchmaneelumka et al. [Petchmaneelumka et al., 2017] propose the use of a circuit based on transconductance amplifiers and a sample-and-hold module, improving thermal stability without adding complexity to the system.

The proposed circuit does not require a low-pass filter. Therefore, fast responses are obtained. They also use a sample-and-hold approach, combined with a direct sum of the secondary signals, achieving accuracy without the need for additional filtering or digital processing [Petchmaneelumka et al., 2018].

Bengtsson [Bengtsson, 2018] presents a low-cost, high-resolution signal conditioning solution for LVDT.

Other works focus on integrated circuit-based solutions. Liu and Bu [Liu & Bu, 2013] describe a design using the AD598 integrated circuit. It integrates excitation, demodulation and continuous output functions, achieving a compact and accurate design with few external components. In their work, Zhang et al. [Zhang et al., 2022] propose a measurement system with an LVDT and a self-holding circuit to measure micro-displacements in satellites.

From a more innovative approach, Songsuwankit et al. [Songsuwankit et al., 2024] present a circuit that eliminates the need for an external oscillator. It takes advantage of the self-oscillation of the primary winding and uses a phase-locked loop [PLL] control system to obtain a signal proportional to the displacement. Similarly, Raghunath et al. [Raghunath et al., 2019] propose a digital system implemented using a specific integrated circuit [ASIC].

The linearity and dynamic response of the sensor are improved through closed-loop control and synchronous demodulation techniques.

Finally, Fan et al. [Fan et al., 2025] introduce an advanced non-linear compensation technique using artificial intelligence, employing a neural network with optimisation algorithms. This significantly reduces measurement error and extends the useful range of the sensor.

Although there are studies related to various parameters of the AM manufacturing process and the effect on its mechanical properties, it is necessary to measure its behaviour as a final product. To this end, the use of LVDT sensors, which are widely recognised in metrological applications, is proposed. One of the challenges they present is signal design and conditioning.

The aim of this work is to implement an LVDT sensor to measure the viscoelastic deformation of parts manufactured using additive manufacturing. A graphical interface is required to visualise and save the readings generated during the tests. This system must be low cost.

## 2. Problem statement

Additive manufacturing has a major impact on the way new products are created. This sector is expected to continue growing. The most commonly used materials are PLA, ABS and PETG. These are polymers, which have viscoelastic behaviour, meaning that when a load is applied, they will continue to deform over time. Currently, data has been reported on the printing parameters that affect mechanical properties.

In general, they report information on tensile strength and fatigue. Information on their viscoelastic behaviour is lacking. On the other hand, there are LVDT displacement sensors with data acquisition systems that can be purchased commercially. However, their cost is high. There are also reports with proposals for low-cost circuit designs and others with higher costs with integrated circuits that allow for more compact designs. In general, they focus on obtaining more accurate readings, but do not discuss their implementation in the phenomenon of viscoelasticity.

It is relevant for the design of products manufactured with additive manufacturing to know the viscoelastic behaviour.

For this purpose, devices that measure displacement can be used. However, it would be uneconomical to take readings and record them at all times.

One solution is to create a system that measures the displacement of AM-produced components over time and stores this data. For the reasons outlined above, it is important to develop a low-cost system that allows real-time visualisation and acquisition of displacement data over time in atomic form for parts created with additive manufacturing.

This allows products to be designed taking into account the phenomenon of viscoelasticity.

## 3. Methodology

To develop the project, the following steps were taken after the documentary research:

1. Electronic circuit design
2. Hardware
3. Characterisation and calibration of the LVDT sensor
4. Interface development
5. Functional testing

## 4. Development

### 4.1 Electronic circuit design

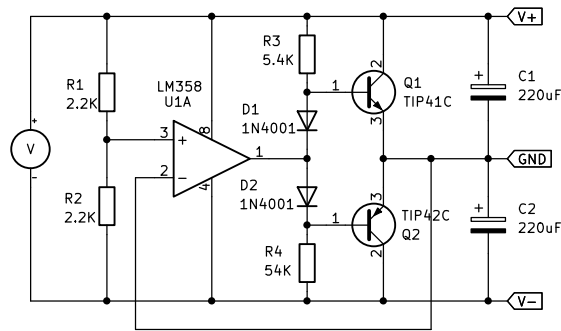
The electronic system developed allows for the excitation, conditioning and reading of the signal from an LVD sensor. The main stages of the circuit are:

- Symmetrical source circuit
- Excitation circuit for the LVDT sensor
- Full-wave precision rectifier
- Low-pass filter
- Offset and amplification adjustment

### Symmetrical source circuit

A symmetrical source was designed to power the circuit from a simple 15 V DC source. A symmetrical power supply was chosen in order to obtain both positive and negative signals.

This decision facilitated the interpretation of the sensor's behaviour, as it allowed for a more intuitive visualisation of the core's displacement around a reference position. **Figure 1** shows the design of the symmetrical source circuit.

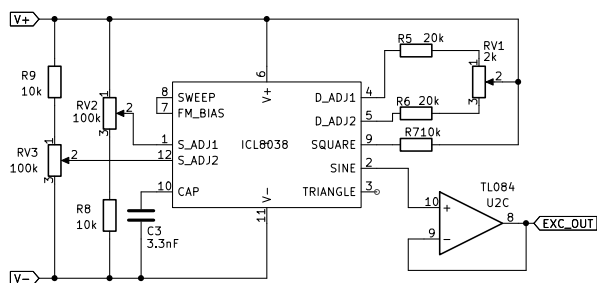
**Box 1****Figure 1**

Symmetrical source circuit.

*Own source***Excitation circuit for the LVDT sensor**

The excitation signal was generated using the ICL8038 integrated circuit as shown in **Figure 2**, configured according to the datasheet recommendations to obtain a sine wave with minimum distortion [Intersil, 2001]. Because the LVDT sensor used has a recommended optimum operating frequency of 5 Hz, this frequency set the values of the associated passive components in the generator circuit.

The resulting sinewave signal was applied to the primary winding of the LVDT via a voltage follower, in order to maintain a stable signal delivery.

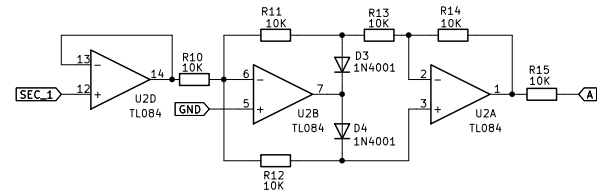
**Box 2****Figure 2**

Excitation circuit for the LVDT sensor.

*Own source***Full wave precision rectifier**

For the conditioning of the signals coming from the secondary windings, two full-wave precision rectifiers were used [see Figure 3].

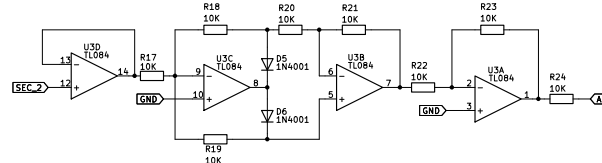
This was based on operational amplifiers and diodes, following a widely used connection for analogue processing of weak signals. For more information see reference [Franco, 2015].

**Box 3****Figure 3**

Full-wave precision rectifier.

*Own source*

One of the rectified signals was inverted [see Figure 4] by means of an additional stage to obtain the difference between the outputs of the secondaries. In this way it was possible to obtain an incremental signal proportional to the displacement of the core with respect to its initial position. The use of two rectifiers, one with an inverting stage, allows the direct addition of both signals.

**Box 4****Figure 4**

Precision rectifier with output inverter stage.

*Own source***Low-pass filter**

Subsequently, the signal was filtered using a first-order low-pass filter [see Figure 5] with a cut-off frequency of 9 kHz. The value of the filter components was calculated using Equation [1] that relates the ripple factor to the capacitor, which facilitates the choice of suitable values without compromising filter performance and response time. For more information see references [Horowitz & Hill, 2015] and [Sánchez Almeida, 2013].

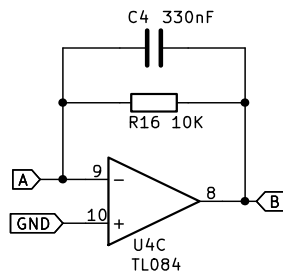
$$C = \frac{1}{4\sqrt{3}f_r(FR)R} \quad [1]$$

$$= \frac{1}{4\sqrt{3}(9000)(0.005)(10000)}$$

$$= 0.3207 \mu F$$

Where:

 $C$  is the value of the capacitor [ $\mu F$ ] $f_r$  is the cut-off frequency [Hz] $FR$  is the ripple factor [dimensionless] $R$  is the resistance value [ $\Omega$ ]

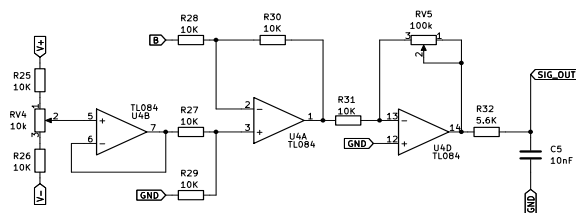
**Box 5****Figure 5**

Low-pass filter.

*Own source***Offset and amplification adjustment**

Since the filtered signal had a negative offset, an adjustment stage was incorporated using a subtractor amplifier with an adjustable reference generated by a potentiometer.

This stage made it possible to compensate the offset so that the output is zero at the initial position of the core. To adapt the signal level to the input range of the microcontroller [0-5 V], an amplification stage with a variable gain of up to 10 times was added, followed by a passive low-pass filter that attenuates the noise introduced by the amplification [see **Figure 6**].

**Box 6****Figure 6**

Offset and amplification adjustment.

**4.2 Hardware****PCB**

The circuit design was created using KiCAD software. A single-layer board was designed and jumpers were incorporated. Figure 7 shows the copper traces in blue and the jumpers in red.

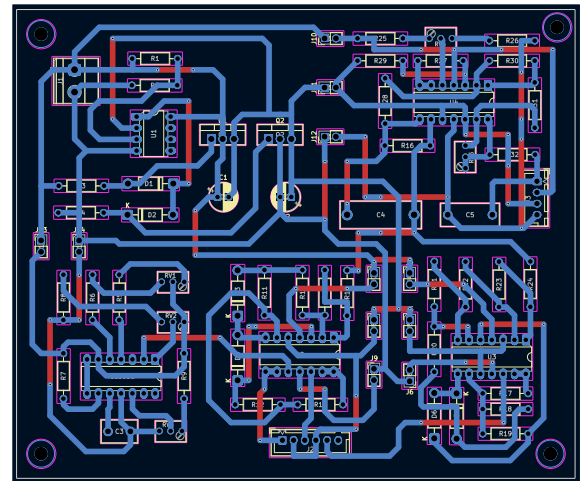
The components were organised into five functional modules: symmetrical power supply, signal generator, precision rectifiers, and the filtering and amplification stage. The board was manufactured using LPKF ProtoMat S104 equipment [CNC equipment for PCB machining].

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The final dimensions of the PCB were 125 mm × 105 mm.

**Box 7****Figure 7**

Printed circuit board [PCB] design.

*Own source***Data acquisition system with microcontroller**

An Arduino Nano board, which incorporates the ATmega328P microcontroller, was used to acquire data from the LVDT sensor. This was due to its ease of programming, low cost, and sufficient resolution for the purpose of this work.

This microcontroller incorporates a 10-bit analogue-to-digital converter [ADC], which allows signals in the range of 0 to 5 V to be discretised with a resolution of approximately 4.88 mV per unit.

The analogue signal from the conditioning circuit is connected to pin A0 of the Arduino. To reduce noise, the implemented code averages 30 consecutive readings from that pin, thus obtaining a more stable signal measurement. A button connected to digital pin D2 was also implemented, configured with the microcontroller's internal pull-up resistor.

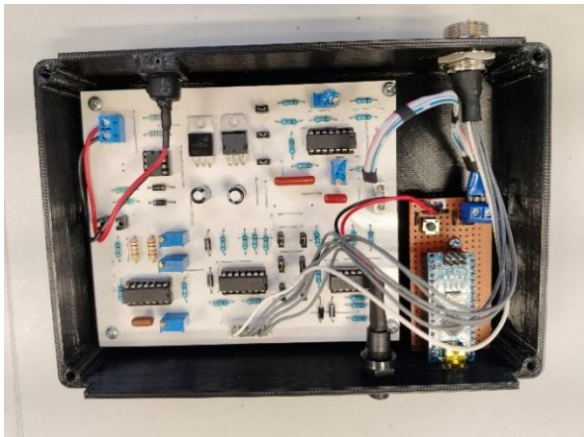
When this button is pressed, the system records the current position as a new reference point or 'zero', allowing the user to reset the displacement reference.

The acquisition frequency was set at one reading per second [1 Hz]. The data obtained is transmitted via the serial port to a graphical interface developed in Python, from which it can be viewed in real time and stored for later analysis.

### Housing and layout of the electronic system

To protect the system's electronic components, a housing was designed to contain the PCB manufactured with the components and the microcontroller during use, thus ensuring safe handling of the device. In addition, the connection to the LVDT sensor is improved [see Figure 8].

#### Box 8



**Figure 8**

Housing and electronics layout.

*Own source*

### 4.3 LVDT sensor characterisation and calibration

The LVDT sensor was characterised under controlled conditions. This was done following the guidelines established by ISO/IEC 17025 and ISO 9513. The former establishes general requirements for the competence of testing and calibration laboratories [ISO, 2017]; while the latter specifies a method for the static calibration of extensometer systems used in uniaxial testing, including axial and diametral extensometer systems [ISO, 2012].

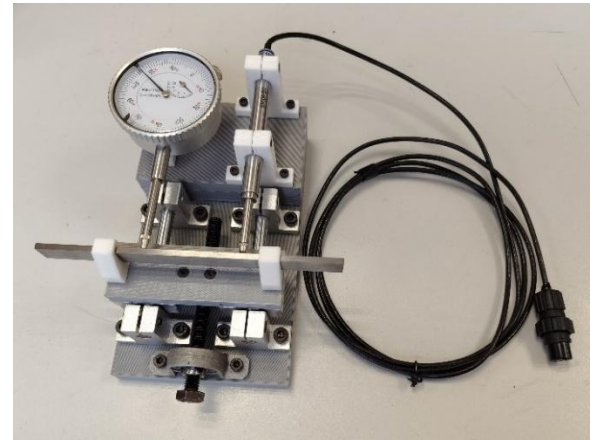
Some environmental factors mentioned by ISO/IEC 17025, such as temperature, vibrations or electromagnetic disturbances, could not be strictly controlled.

Nevertheless, efforts were made to comply with the related essential principles such as methodology, mechanical assembly and traceability of the reference standard.

Figure 9 shows the complete LVDT characterisation device. It allowed to compare the signal delivered by the LVDT with the displacements recorded by a dial indicator. The resolution of the dial indicator is 0.01 mm.

The instruments were mounted horizontally on a rigid base, ensuring that their stems remained parallel, aligned and with a common contact point.

#### Box 9



**Figure 9**

Characterisation support device.

*Own source*

The displacement was generated by a screw pushing a sliding table guided by linear bearings. A ground steel parallel was placed on top of this, which serves as a simultaneous contact surface for the two transducers.

This configuration meets the requirements of ISO 9513 for structural rigidity, motion control and mounting stability.

The characterisation process consisted of incremental displacements of 1 mm, starting from the position where the parallel made simultaneous contact with both instruments until a total travel of 22 mm was reached.

At each point, both the reading of the caratula indicator and the signal delivered by the LVDT sensor were recorded. According to ISO 9513, the number of calibration points should be defined based on Eq. [2]:

$$\frac{L_{max}}{L_{min}} = \frac{22mm}{1mm} = 22 \quad [2]$$

Where:

$L_{max}$  is the maximum displacement

$L_{min}$  is the minimum displacement

This places the system in category [b] of that standard, where at least two calibration ranges and five measurements per range are required.

The applied procedure met this criterion, covering the entire operating range of the sensor without omitting critical regions. **Figure 10** shows the scatter plot of the data and the fit line obtained by linear regression. Equation 3 shows the relationship:

$$y = 0.0221x - 0.5548 \quad [3]$$

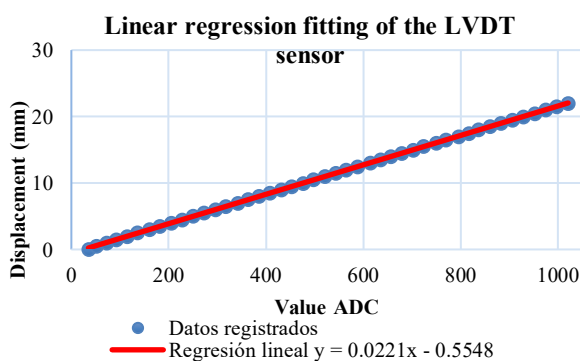
Where:

$y$  is the displacement in millimetres

$x$  is the average value read by the ADC

This equation was subsequently implemented in the microcontroller for the conversion of ADC units to mm. As can be seen, the sensor presented a highly consistent linear behaviour.

### Box 10



**Figure 10**

Dispersion of the obtained data and the fit line.

*Own source*

### 4.4 Graphical interface of the data acquisition system

The graphical interface developed allows visualisation of the LVDT sensor readings. Also, a file with displacement and time information can be generated. This was done in Python, using the Tkinter libraries to build the GUI, Matplotlib for the graphical visualisation of the data and PySerial to establish serial communication with the Arduino Nano. The **Figure 11** shows the interface. The left side consists of a control panel, which allows selecting the communication port, starting or ending a test and displaying the elapsed time.

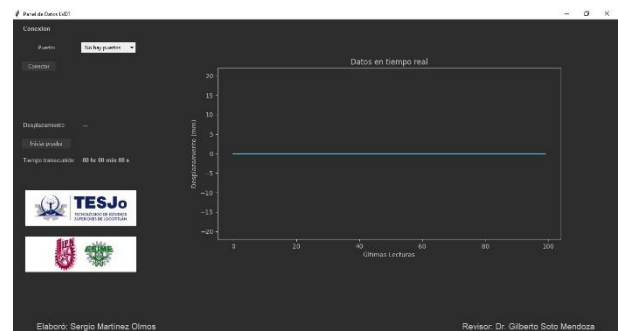
The right side includes a graph that plots the displacements as a function of time, showing the last readings for easy visual tracking. During a test, the data received from the microcontroller is dynamically updated on the graph. At the end, the user can save the results in a CSV file.

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### Box 11



**Figure 11**

Graphical interface of the measurement system.

*Own source*

### 4.5 Functional test

A PLA cantilever beam was tested by applying a constant load of 5.3 kg on the specimen for a total time of 6 hours.

Figure 12. The beam has a length of 210 mm, the restraint is 20 mm, from the left end of the beam the load is located at 10 mm to the right and the sensor at 60 mm to the right. The cross section of the beam is 8 mm wide and 16 mm high.

### Box 12



**Figure 12**

Test run.

*Own source*

## 5. Analysis of Results

Once the equation characterising the behaviour of the LVDT was obtained, it was loaded into the code. Subsequently, the readings obtained with this LVDT sensor were compared with those of the dial indicator.

The latter was used as a reference instrument. Displacements were applied in 1 mm increments from 0 to 22 mm. Table 1 presents the measurements obtained by both devices, as well as the difference in readings between them. The maximum difference was 0.10 mm

### Box 13

**Table 1**

Comparison of measurements between a Dial Indicator and the LVDT.

Front cover indicator, mm	LVDT, mm	Difference, mm
0.00	0.00	0.00
1.00	0.99	0.01
2.00	2.03	0.06
---	---	---
9.00	9.10	0.10
10.00	9.98	0.02
11.00	10.92	0.08
---	---	---
20.00	20.09	0.09
21.00	21.10	0.10
22.00	22.10	0.10

When comparing the maximum percentage error with other works, it was found that Rerkratn et al. [Rerkratn et al., 2020] report a maximum error of 1.1% and later this author presented another with a maximum error of 0.295 % [see Table 2]. The maximum error presented in this work is 0.46 %.

### Box 14

**Table 2**

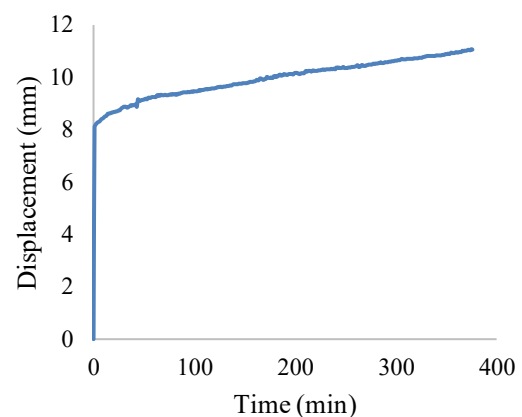
Comparison of the percentage of measurement error.

Autor	Measuring range [mm]	Maximum error [mm]	Maximum error [%]
Olmos et al.	22.00	0.10	0.46
Rerkratn et al. [Rerkratn et al., 2020]	20.00	0.220	1.10
Fan et al. [Fan et al., 2025]	16.00	0.042	0.27
Bengtsson et al. [Bengtsson, 2018]	12.70	0.006	0.047
Songsuwankit et al. [Songsuwankit et al., 2024]	8.00	0.034	0.42
Rerkratn et al. [Rerkratn et al., 2022]	6.20	0.018	0.295
Ran and Hui [Liu & Bu, 2013]	5.80	0.016	0.27

The result of the function test is shown in Figure 13, where the vertical axis represents the displacement and the horizontal axis corresponds to the time. The sensor was set to zero with no load, when the load was applied it displaced approximately 8 mm [elastic deformation].

Subsequently, the material continued to deform over time. At the end of the test, the total displacement recorded was 11.08 mm, which represents a viscous deformation of 3.08 mm.

### Box 15



**Figure 13**

Result of the cantilever beam test.

*Own source*

## Conclusions

An LVDT sensor was implemented as a tool to measure the viscoelastic deformation of parts manufactured using additive manufacturing. The graphical interface allows real-time displacement to be visualised. It also has the function of saving displacement information as a function of time in a CSV file. The characterisation of the LVDT sensor allowed an equation to be created with linear regression adjustment.

When directly comparing the LVDT sensor readings with a dial indicator, the maximum variation obtained was 0.1 mm. The sensor's measurement range is 22 mm and it has a maximum error of 0.46%. The application example was a PLA beam in which an elastic deformation of 8 mm and a viscous deformation of 3.08 mm were found in a time of 6 hours. The proposal represents an economical manufacturing version. It was also found that the integrated AD598 can be used, which allows for a more compact circuit, although it has a higher cost.

## Declarations

## Conflict of interest

The authors declare that they have no conflict of interest.

They have no financial interests or personal relationships that could have influenced this article.

## Contribution of the authors

*Martínez-Olmos, Sergio*: Contributed to the research, methodology, formal analysis, software, and writing.

*Soto-Mendoza, Gilberto*: Contributed to the project idea, project management, supervision, methodology, validation, review, and writing.

*Hernández-Gómez, Luis Héctor*: Contributed to the project idea, review, and editing.

*Mier-Quiroga, Luis Antonio*: Review and editing.

## Availability of data and materials

The data generated during this study are available from the corresponding author upon reasonable request.

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