Development and Application of Linear Variable Differential Transformer (LVDT) Sensors for the Structural Health Monitoring of an Urban Railway Bridge in Vietnam

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ABSTRACT

Measuring the structure's displacement plays a very important role in ensuring the safe operation of railway bridges in general and urban railway bridges in particular. In Vietnam, traditional methods using high-precision mechanical gauges have been used to measure the displacement of railway bridges. However, these methods need a lot of effort in installation and traffic control during implementation. These methods are based on the static principle: The test loads are placed on the bridge structure, and then the structure's displacement is observed. The safety assessment and analysis results are guaranteed by multiplying the dynamic coefficients, leading to some assessments that may not be close to the actual exploitation of the bridge structure. Therefore, the current study presents a new solution for measuring the displacement of railway bridge structures. This method uses Linear Variable Differential Transformer (LVDT) sensors to record the continuous displacement of the structure during the time the train passes over the bridge. Through field measurements combined with a finite element analysis model, the research focuses on developing and applying LVDT sensors in urban railway bridge structure health monitoring. At the same time, the potential of developing this method in Vietnam in the future is evaluated.

Keywords-dynamic displacement; LVDT; urban railway

I. INTRODUCTION

The urban railway is considered the backbone of the transport infrastructure system of any developed city in the world [1, 2]. Hanoi is no exception. Moreover, the need to build an urban railway network is becoming more urgent than ever when the pressure of traffic congestion and environmental pollution increasingly weighs on the narrow infrastructure fund of the Vietnamese capital. Putting into operation the urban railway network is expected not only to change the urban appearance of Hanoi and reduce congestion and accidents, but to a greater extent, it will change the habit of using public transport and the traffic culture of the people in the future. Currently, Hanoi is expected to have 8 urban railway lines totaling about 318 km. This is the first elevated urban railway system in Vietnam. The first two railway lines built were Line 2A, section Cat Linh - Ha Dong, and Line 3, section Nhon - Hanoi Railway Station. Therefore, timely detection and repair of problems related to the span structure are extremely necessary because the route is built in the roadway of densely populated and high-traffic routes, making repairs on a large scale difficult. One of the causes affecting the damage of partial span structures is also due to excessive deformation. In the management and understanding of both new infrastructure using new technologies and decaying infrastructure, in particular bridges and pavements, field testing is a topic that is becoming more and more crucial. After an isolated and potentially catastrophic event, there is a requirement for precise and expensive diagnostics, load distribution verification, actual load-carrying capacity calculation, and structural performance evaluation. This helps to improve the efficiency of exploitation and increase the safety of railway infrastructure. At the same time, the regular assessment will take timely remedial measures to avoid disrupting traffic and not affecting other related industries.

Railroad managers inspect bridges regularly to ensure their safety and prevent derailments, delays in network operation, and loss of time and resources. The majority of contemporary bridge inspection techniques call for visual inspection [3] which often is not reliable [4-6]. The operational capacities of a bridge can be determined with the help of Structural Health Monitoring (SHM) [7]. Railroad management organizations are interested in measuring parameters and responses under loads to objectively inform the safety and expansion of their operations. An essential component of SHM is the measurement of bridge displacement under dynamic loads brought on by train motion [8-10]. The measured deflection response can be incorporated into a bridge finite element model to calculate back residual capacity, compare the in-service behavior with the intended behavior, or determine the degree of damage. According to the commonly used traditional method, displacement at a position on the structure is measured through static testing. The load is calculated and placed in the most unfavorable position of the structure [11, 12]. The equipment used here is high-precision mechanical gauges or high-precision surveying devices (Figure 1). The above method has relatively accurate results for the test loads. However, there are a few shortcomings in this method. First, in order to perform the static load test, it is necessary to stop the traffic on the road (Figure 2). Second, the measured result is the displacement caused by the test load, not the actual daily load on the bridge. The test load is completely based on the experience and the calculations of the consultant. Therefore, the results do not fully evaluate the entire response of the bridge. Furthermore, this result only represents a specified moment of the bridge, which is usually the maximum value when the test load enters the bridge. If an abnormality is present in the dynamic response, this result will usually not be accurately evaluated [13].


(a) (b)

Fig. 1. Measure displacement: (a) Use of high-precision mechanical gauges, (b). surveying devices.

Fig. 2. Static load test to inspection bridge.

In railway bridges, especially urban railway bridges, it is impossible to mobilize test loads from trains. The only way to measure displacement of a bridge structure is to measure it during its operation. Traditional methods are not efficient enough and the obtained results will not have high accuracy. This leads to the need to apply a new type of device to record the dynamic displacement of the structure under the effect of operating loads. Several researchers have developed methods for different types of devices. Authors in [14-16] used accelerometers to measure the horizontal displacement of the structure. The Global Positioning System (GPS) has also been used as a contact sensor to measure displacement [17-19]. Although these methods are relatively modern, the accuracy level is only acceptable. Besides, the equipment investment cost for the above solutions is relatively expensive, often not suitable for management units.

LVDT has been applied to many projects around the world [20], even though in Vietnam, this device is still in limited use. This study proposes the use of LVDT sensors installed on the urban railway bridge structure to measure the displacement under the effect of the train load in operation. System validation and development were conducted through field experiments and finite element modeling. Finally, barriers to using LVDT for field applications were identified and possible solutions to each problem were proposed.

II. LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)

A. Introducing LVDT

The LVDT is an essential kind of inductive transducer. Inductive transducers are those that operate on the idea of a transduction mechanism. In essence, an LVDT is a position sensor that can pick up on linear motion or vibrations and translate them into electrical signals or a fluctuating electrical current. The LVDT sensor transforms the linear movement of the object to which it is connected into a variable electrical signal that corresponds to that movement. The movement might range from 0-0.5 mm to 0-1000 mm in laboratory, industrial, and underwater contexts. This design has been in use for many years for the precise measurement of displacement and for positioning control in tight loops.

B. The LVDT Working Principle

Similar to a transformer, an LVDT has one main winding, designated P, and two secondary windings, designated S1 and S2. The primary and secondary windings are wound on a former, which is a hollow cylindrical structure (Figure 3). The former is frequently made of glass-reinforced polymer that has been clad in cylindrical steel and wrapped in a porous material. The primary winding of the cylindrical former is in the middle, and on either side of it, two secondary windings are placed evenly separated from the center. Both secondary windings have the same number of turns and are connected to one another in series opposition, meaning that they are wound in different directions yet are connected to one another.

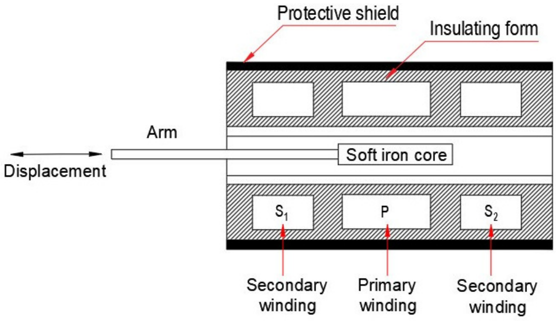


Fig. 3. Structure of LVDT

The electromagnetic law of Faraday serves as the foundation for how LVDTs function. An alternating magnetic field is produced when the primary winding of the LVDT is connected to the AC power source; this field generates an electromotive force (emf) in the secondary windings. The secondary signal alters as the core moves in this region (Figure 4(a)). When the core is positioned in the center and the two secondary windings are arranged and connected in a specified configuration (push-pull mode), a zero signal is obtained. The signal grows as the core is moved away from this location in either direction (Figure 4(b)). The signal output has a linear relationship with the actual mechanical movement of the core as long as the windings are wound with a specific level of precision. A phase-sensitive demodulator that switches at the same frequency as the primary energizing supply then processes the secondary output signal. This yields a final output that, following rectification and filtering, provides a DC or 4-20 mA output proportional to the core movement and also specifies its direction, positive or negative from the center zero point (Figure 4(c)).

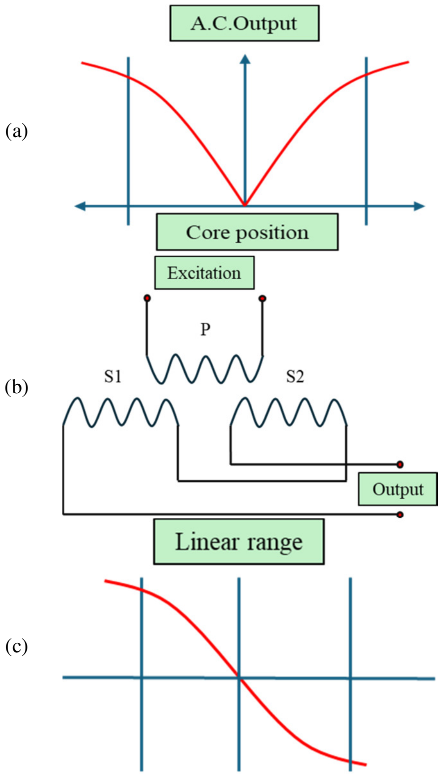


Fig. 4. The LVDT working principle.

C. Advantages of the LVDT

One of the most outstanding features of the LVDT over other mechanical measuring devices is the absence of friction. This is because there is no direct contact between the moving core and the other parts. This results in the device not being easily damaged. In terms of longevity, LVDT will be more durable than other devices. The LVDT does not need to employ an amplifier to amplify the signals because of its powerful output signal and sensitivity to even very small displacements. This is very suitable for monitoring and measuring structures with large displacements such as bridges. They typically use less than 1 W of electricity and exhibit less hysteresis loss, which improves their reliability. LVDT sensors are small and lightweight, they can be readily handled and aligned to meet requirements. In spite of their tiny size and lightweight nature, LVDT can withstand mechanical shocks and vibrations. The absolute value is provided by the LVDT. It implies that in the event of an unexpected power outage, the LVDT does not lose its location data. If the measurement is redone, the output value stays the same as it was before to the power outage.

From the above advantages, the application and development of LVDT in dynamic measurement and monitoring of urban railway bridge structures is completely appropriate.

III. CASE STUDY

A. Hanoi Urban Railway, Cat Linh Ha Dong Line

The Hanoi Urban Railway system includes the urban railway line connecting Cat Linh and Ha Dong (Figure 5). The Cat Linh - Ha Dong route has a total length of 13021.48 m. The entire route is built on high (overpass form). The main span structure used is a combination of simple beams supported on piers. The span length main forms are 18.5, 20, 26, 29, 30, 32 m span structure with box cross section. Cat Linh - Ha Dong urban railway line is designed to ensure a harmonious connection with other urban railway lines in the future and bus stations along the route.

Fig. 5. The Cat Linh-Ha Dong urban railway bridge.

B. Equipment Selection

As described above, the equipment used here is two LVDT sensors and dedicated cables for signal transmission (Figure 6).

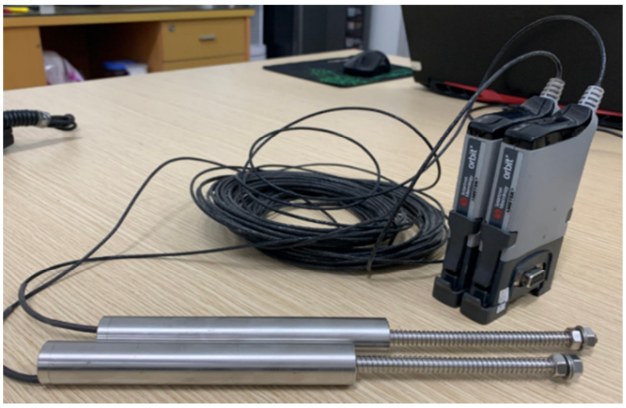
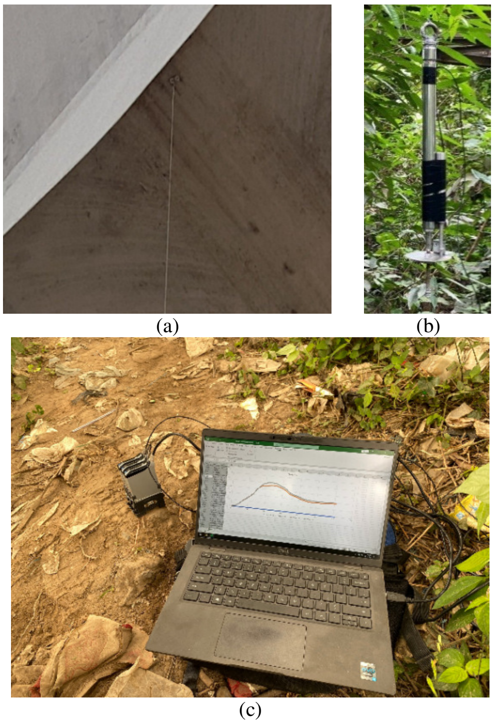


Fig. 6. LVDT sensors and cables.

In addition to the main part, LVDT displacement sensors, accessories such as jigs, and fixing devices are also equipped. A dedicated computer is used throughout the entire experiment. To ensure the objectivity of the measurement results, a number of mechanical devices have been used and verified in many experiments (high-precision mechanical gauges).

C. Field test

At the center of a box girder span, a mechanical measuring device and an LVDT sensor are installed (Figure 7).



(a) (b) (c)

Fig. 7. Installation of the measuring equipment: (a) high-precision mechanical gauges, (b) LVDT sensor, (c) data recording.

A laptop is used with integrated measurement software NI-LabVIEW 2014 (32-bit). It collects signals from the measuring heads during measurement and saves them as files. Displacement is measured in both vertical and horizontal direction of the structure.

D. Creation of the Finite Element Model

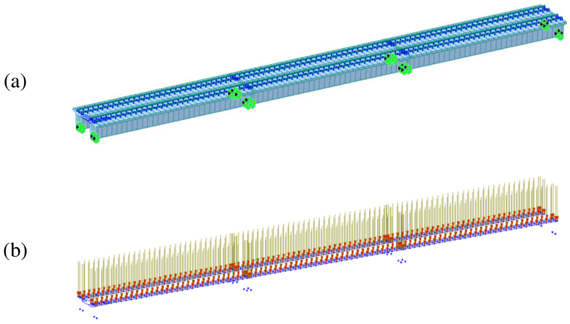


Fig. 8. The finite element model of the structure.

A finite element model was built based on the surveyed conditions and the profile of the project. The simulated mobile load is a train moving at the speed according to the operating profile. The elements used are in the form of beams, the load is the moving load of the train.

IV. RESULTS AND DISCUSSION

The simulation and experimental results are shown in Figures 9 and 10.

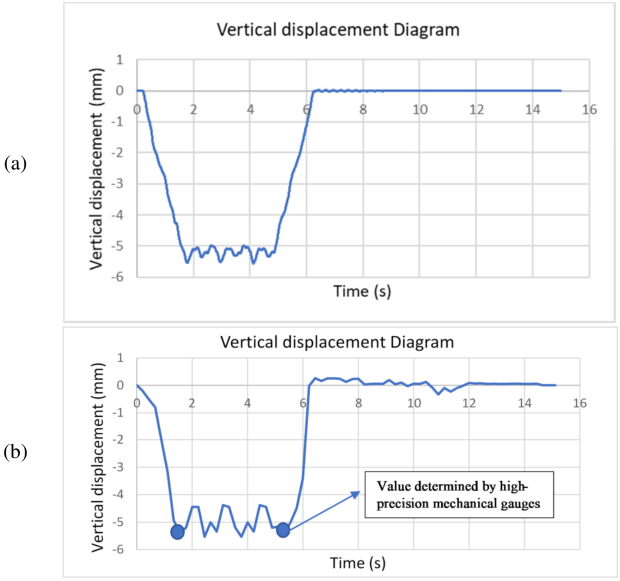


Fig. 9. Vertical displacement results. (a) Simulation, (b) experiment.

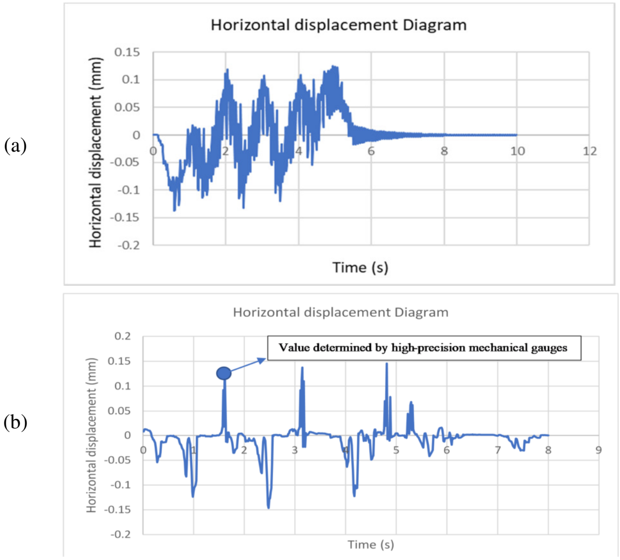


Fig. 10. Horizontal displacement results. (a) Simulation, (b) experiment.

Based on the results obtained from the model and the experiment, it can be seen that the measurement results from the LVDT and the model are similar. The LVDT sensor allows to record structural displacement data during the entire time the train is acting on the structure. Meanwhile, high-precision mechanical gauges only allow a maximum value to be observed. The comparison results between the model, the LVDT sensor and the high-precision mechanical gauges are similar, showing the reliability of the LVDT sensor. The maximum vertical displacement value in the obtained model is 5.48 mm, LVDT is 5.68 mm, and high-precision mechanical gauges are 5.5 mm. Because it is done automatically and has a higher sensitivity than human observation to mechanical equipment, LVDT gives more accurate results.

V. CONCLUSION

Structural displacement measurement plays a significant role in ensuring the safe operation of urban railway bridges. This study proposes the use of LVDT sensors in structural health monitoring (specifically displacement monitoring) on urban railway bridges. The displacement monitoring by LVDT is applied and gives good results on the actual bridge. Field tests are designed for the application and development of LVDT in structural displacement monitoring. The experiment confirms the accuracy of the applied method and is combined with the results of the finite element simulation. Through testing on a real bridge, the obtained results show the potential of LVDT when applied outside the laboratory. Although the initial investment cost may seem higher than that of traditional solutions, when it comes to long-term and performance aspects, the LVDT shows its effectiveness when applied in practice. Here are some of the main conclusions of the current study:

- Applying LVDT in continuous displacement monitoring of structures gives better results than other traditional methods. The obtained results are similar to the modeling results and the accuracy is greater than that of the traditional methods used in Vietnam.
- The result from LVDT is in the form of continuous data, and not discrete as when using high-precision mechanical gauges. This leads to the easy observation of structural irregularities over long periods of time
- The results obtained from LVDT can be used for big data applications in structural health monitoring. Specifically, time series data can be used as an input to train artificial intelligence networks that are being developed recently.

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