Automatic measurement and warning of tension force reduction in a PT tendon using eddy current sensing

Ji-Min Kim, Jun Lee, Hoon Sohn⁎

Department of Civil and Environmental Engineering, KAIST, Daejeon 34141, South Korea

A R T I C L E   I N F O

Keywords:
Post-tensioning tendon
Pre-stressing strand
Tension force loss
Eddy current measurement
Nondestructive testing and evaluation
Low power inspection

A B S T R A C T

Post-tensioning (PT) using a bundle of pre-stressed strands is a critical process for assembling pre-fabricated and modularized bridge members. However, the tension force gradually diminishes over time due to such factors as corrosion, creep, and steel relaxation. Such changes compromise the overall safety of such structures. In this study, an eddy-current-based tension-force-loss warning (EC-TFLW) technique is proposed to detect and warn automatically of excessive loss of tension force in a PT tendon. A ring-type eddy-current sensor (ECS) is mounted on the outer surface of a wedge holding a tendon, and the level of eddy current measured by the ECS is related to the tension force of the tendon. The advantages of the proposed technique include: (1) low power consumption, (2) low cost, (3) simple installation, and (4) automated warning. The performance of the proposed EC-TFLW technique was validated experimentally in a full-scale lab test of a 3.3-m long, 15.2-mm diameter, mono-strand tendon that was tensioned using a universal testing machine (from 20 to 180 kN). Statistical hypothesis testing using the chi-square distribution was applied to the measured eddy current signals, and if the decline in tension exceeded a certain level, a warning was sent out automatically.

1. Introduction

The use of pre-fabricated and modularized components, such as concrete slabs and girders, is becoming popular because of their contribution to the improved quality and rapid construction of bridge structures. Furthermore, post-tensioning (PT) construction has been broadly used to assemble pre-fabricated concrete bridge segments using a bundle of pre-stressed strands which is also called as PT tendon. Fig. 1 shows a schematic overview of PT construction. When the PT tendon is pulled using a hydraulic jack, the PT tendon applies compression force to the concrete bridge segments and those segments behave like a single concrete girder as shown in Fig. 1.

Once the PT construction is completed, the tension force of the PT tendon gradually declines over time. The reduction of the tension force can be categorized as either (1) immediate loss or (2) time-dependent decrease [1]. The immediate loss results from elastic shortening of a concrete body and friction force at the tendon-concrete contact face. Time-dependent decrease is mainly caused by steel relaxation, steel corrosion, and concrete creep. Excessive loss of tension force can lead to a catastrophic collapse of the entire bridge system, and such events have been reported previously: Ynys-y-Gwas Bridge, UK (1985), Melle Bridge, Belgium (1992), Saint Stefano Bridge, Italy (1999) and Lowe’s Motor Speedway Footbridge, USA (2000) [2–4].

Because sustaining a certain level of tension force of the PT tendon is essential to assure the integrity of a bridge, and to prevent catastrophic failure of the bridge, several techniques have been proposed to inspect the tension force of the PT tendon (as described in Fig. 2). For example, an electromagnetic (EM) sensor utilizing the Villari effect (inverse magneto-mechanical effect) of steel [5,6] was developed to quantitatively estimate the PT tendon force. However, because of the high power requirement in the range of a few hundred Watts, its installation and maintenance can be challenging. More specifically, its applicability for a PT tendon embedded inside concrete is limited because of its bulkiness. Kim et al. [7] and Lan et al. [8] fabricated a tendon with a hole at its center and inserted an optical fiber with distributed Fiber Bragg Grating into the hole to measure the strain variation caused by tension force change [7,8]. However, its installation can be extremely difficult and expensive because a hole must be drilled through the center of the steel wire of the tendon and then the optical fiber must be inserted into the hole. Additionally, piezoceramic [9], strain [10], and eddy current sensors (ECS) [11] with low cost and low power consumption have been explored to evaluate tension force loss. Bartoli et al. [9] utilized piezoceramic transducers to generate and measure ultrasonic waves through a tendon, and analyzed the interwire leakage between the peripheral and the central wires caused by varying the tension force level. However, it is difficult to
attach piezoceramic transducers to the tendon and to maintain a good bond. Furthermore, the travel distance of the ultrasonic waves created by the piezoceramic transducers is often quite limited. Abdullah et al. [10] attached strain gauges to the surface of an anchor head, and related local strain measurement to the tendon force. This technique was tested only for the breakage of several tendons, and its sensitivity to initial tendon force reduction was not reported. Ricken et al. [11] installed an eddy current coil directly on the surface of a steel tendon, producing magnetic flux passing through the tendon. Then, they investigated the relationship between the change of magnetic flux density and the tendon force. However, direct installation of the eddy-current coil inevitably brings about coil breakage and malfunctions caused by collisions with adjacent tendons, in a multi-tendon system.

In this study, a new way of coupling eddy-current measurement with a PT tendon force is proposed. The variation of the tendon force alters the stress on the exposed surface of a wedge holding the tendon. Then, they investigated on the Villari effect, the altered surface stress changes the intensity of the eddy current and the corresponding magnetic flux is...
measured by an ECS attached to the wedge surface. Note that the proposed EC-TFLW technique operates using a power level of only a few hundreds of mW, although the proposed technique utilizes the Villari effect (as do other magnet-based sensing techniques). Finally, the proposed EC-TFLW technique estimates the loss of tension force with respect to its initial force (measured right after construction of the PT tendon), based on the intensity variation of the eddy current. When an excessive loss is detected, the proposed technique sends out a warning signal. The advantages of the proposed EC-TFLW technique includes (1) simple sensor design and installation, (2) low cost and low power consumption, and (3) potential for embedded sensing by installing ECS inside concrete structures.

This paper is organized as follows. The detailed working principle of the proposed EC-TFLW technique is described in Section 2. Then, a hardware system and an automatic warning algorithm for the EC-TFLW technique are developed in Section 3. The performance of the EC-TFLW technique is validated experimentally in Section 4, and a brief summary with discussion of future improvements is offered in Section 5.

2. Working principle of an eddy-current-based tension-force-loss warning (EC-TFLW) technique

The EC-TFLW technique was developed based on the premise that variation of the tendon force alters the stress on the exposed surface of a wedge holding the tendon. Fig. 3 illustrates how compressive force is introduced to, and accumulated on, the wedge surface as the tension force (T) increases. Fig. 3(a) shows a wedge simply holding an unloaded tendon; thus, there is no force on the wedge surface yet. As low-intensity tension is applied to the tendon, the wedge slides into the wedge cavity of an anchor head, and the wedge is subjected to compression force (C) as shown in Fig. 3(b). As the tension force of the tendon is gradually increased, the compressive force is intensified on the wedge surface, as shown in Fig. 3(c) and (d). Note that the actual force distribution over the volume of the wedge may be different from what is shown in Fig. 3. For simplicity, a uniform distribution is illustrated.

To estimate the loss of tension force from variation of the stress on the wedge surface, the Villari effect of ferromagnetic materials is utilized. The Villari effect describes how variation of the stress level in ferromagnetic materials alters the magnetic permeability, as shown in Eq. (1) [12–15].

\[
S = \varepsilon \Psi + dH \\
B = d\Psi + \mu H
\]

where \(S\) and \(\Psi\) are strain and stress, and \(B\) and \(H\) are magnetic flux density and the applied magnetic field strength, respectively. For simplicity, a linear magneto-mechanical relation for low-intensity magnetic field strength was assumed in Eq. (1). Note that Eq. (1) becomes invalid for high-intensity magnetic field strength [12]. The magneto-mechanical coupling is defined through piezomagnetic cross-coupling coefficients, \(d\) and \(d^*\). Here, \(sH\) is mechanical compliance at constant magnetic field strength, and \(\mu\) is magnetic permeability at constant stress. According to Eq. (1), the change of stress \(\Psi\) results in alternations of the magnetic permeability \(\mu\). Subsequently, the magnetic flux density \(B\) even under the constant magnetic field strength \(H\).

The detailed working principle of the proposed EC-TFLW technique is as follows. An ECS is mounted on the exposed surface of the wedge as shown in Fig. 4(a). When an AC voltage is applied to the ECS, a magnetic field with strength \(H\) is produced, and a magnetic flux with density \(B\) flows through the wedge made of a ferromagnetic stainless steel. Consequently, an eddy current is generated on the wedge surface, as shown in Fig. 4(b), in the direction opposite to the changing of the magnetic flux density \(B\) [14]. As the tension force is reduced, the compressive stress on the wedge surface decreases, altering its magnetic permeability \(\mu\) based on Villari effect [12,13]. Consequently, the intensity of the eddy current induced on the wedge surface varies, and the sensing part of the ECS picks up the variation of the eddy current [16]. By comparing the variation of the eddy current with its initial value, the tension force loss of the tendon can be detected.

3. Development of the EC-TFLW technique

First, an EC-TFLW hardware system and ring-type ECS were designed and fabricated. Then, an automatic warning algorithm was developed to detect the loss of excessive tension force, using statistical hypothesis testing.

3.1. Development of the EC-TFLW hardware system

The developed EC-TFLW hardware consists of an arbitrary waveform generator (AWG), a digitizer, a control unit, and an ECS. Slot-type commercial products (i.e., NI PXI-5421, NI PXI-5122, and NI PXI-
8119 from National Instruments, Inc.) were used for the AWG, the digitizer, and the control unit, respectively. The AWG has 16-bit resolution, 100 MHz sampling frequency for digital-to-analog conversion, and maximum output voltage of ± 6 V. The digitizer can sample eddy current data with 14-bit resolution and 100 MHz sampling frequency. The control unit contains a 2.3 GHz processor and 4 GB RAM for post-processing of the measured data.

The proposed ring-type ECS shown in Fig. 5 is composed of two separate coils, a 135-turn coil with 0.1-mm diameter wire, and a 12-turn coil with 0.08-mm diameter wire. The 135 and 12-turn coils are used as driving and sensing coils, respectively. The sensing coil is located inside of the driving coil, and the overall size of the ECS is less than 20-mm in diameter and 2.0-mm thick. The electrical resistance and inductance of the driving and sensing coils were found to be 20 and 2.5 Ω, and 870 and 7.3 μH, respectively. Note that, because of the simple design of the proposed ECS, the ECS can easily be inserted on the PT tendon sticking out from the anchor head (Fig. 4a), and its insertion does not interfere with the current process of installing PT tendons.

The operation principle of the developed EC-TFLW hardware system is shown in Fig. 6. First, the control unit launches a trigger signal to activate and synchronize the AWG and the digitizer. The AWG generates a linear chirp signal with a frequency bandwidth covering the resonant frequency of the ECS, and applies the chirp signal to the driving coil resulting in alternation of the magnetic field and magnetic flux on the wedge surface. Subsequently, an eddy current is produced on the wedge surface, and the variation of the eddy current caused by reduction of the force on the PT tendon, is measured by the sensing coil of the ECS. Then, the data are digitized and transferred to the control unit. The data transferred to the control unit are analyzed using the tension-force-loss warning algorithm described in the following section.

3.2. Development of the EC-TFLW algorithm

An automatic warning algorithm for excessive loss of tension force was developed, and its overview is provided in Fig. 7. The developed algorithm is composed of two steps: (1) Eddy current measurement at the initial maximum tension force level, and subsequent measurement at an unknown force level, and (2) Automated warning of tension force loss based on hypothesis testing.

3.2.1. Eddy current measurement at the initial maximum tension force level, and subsequent measurement at an unknown force level

Once installation of the PT tendon and ECS was completed, initial measurement of the eddy current was performed. A chirp signal with a pre-described frequency bandwidth was applied to the driving coil of the ECS to generate a magnetic field, of which the penetration depth (δ) through the wedge surface, was computed using Eq. (2) [17].

$$\delta = \frac{\rho}{\sqrt{\mu_\text{r} \mu_0}}$$  (2)

where f denotes the driving frequency in Hz applied to the driving coil, and ρ and μr represent the electric resistivity in Ω m and relative magnetic permeability of a target material, respectively. Here, μ0 is the magnetic permeability in vacuum ($4\pi \times 10^{-7}$ H/m).

This eddy current measurement was repeated n times as described in Step (1) of Fig. 7, after which $X_i(t)$ (i=1,2,...,n), and their averaged response, $\bar{X}(t)$, was computed. Then, the overall variance, $\sigma_0^2$, of all the measured $X_i(t)$ (i=1,2,...,n) with respect to $\bar{X}(t)$ was computed as follows.

$$\sigma_0^2 = \sum_{i=1}^{n} \sum_{j=1}^{m} (X_i(j\Delta t) - \bar{X}(j\Delta t))^2/nm$$  (3)

where $\Delta t$ denotes the time interval of data sampling and m denotes the number of sample points in each measurement.

Later on, identical measurements were repeated n times at an unknown level of tension force, the new measurement was denoted $Y_i(t)$ (i=1,2,...,n), and the corresponding variance, $\sigma_1^2$, was computed as follows.
\[ \sigma_i^2 = \sum_{i=1}^{n} \sum_{j=1}^{m} (Y_{i,j} - X_{i,j})^2 / n \cdot m \] 

(4)

Note that \( \sigma_i^2 \) was computed with respect to \( X(t) \) rather than \( Y(t) \).

### 3.2.2. Automated warning of tension force loss using hypothesis testing

If the tendon force, when measured after a while, is identical to the initial (maximum) value, \( \sigma_1^2 = \sigma_0^2 \). However, as the tension force decreases from its initial value, \( \sigma_1^2 \) will become larger than \( \sigma_0^2 \). Based on this observation, a hypothesis test was formulated to validate the following null hypotheses:

\[
H_0: \sigma_i^2 = \sigma_0^2 \quad \quad H_1: \sigma_i^2 > \sigma_0^2
\] 

(5)

When each entity in Eqs. (3) and (4) is assumed to be a random variable following a normal distribution, \( \sigma_0^2 \) and \( \sigma_1^2 \) follow chi-square distributions. Then, a test statistic, \( \chi^2_{\text{stat}} \), for the hypothesis testing becomes [18]:

\[
\chi^2_{\text{stat}} = \frac{(n - 1) \cdot \sigma_i^2}{\sigma_0^2} \sim \chi^2_{n-1}
\] 

(6)

where \( \chi^2_{n-1} \) denotes a chi-square distribution with \( n-1 \) degree of freedom (DOF), and a threshold corresponding to a certain confidence level is selected from the \((n-1)\) DOF chi-square distribution table, which shows the relationship between \( n \) and \( p \), and the confidence interval.

**Threshold value** = \( \chi^2_{(n-1),(1-\alpha)} \)

(7)

Should the test statistic exceed the threshold value, \( H_0 \) is rejected and a warning signal is automatically sent out.

\[
\chi^2_{\text{stat}} \leq \text{Threshold} \rightarrow \text{Accept } H_0 \quad \quad \chi^2_{\text{stat}} > \text{Threshold} \rightarrow \text{Reject } H_0
\] 

(8)

---

**Fig. 6.** Overview of the developed EC-TFLW hardware system: an AWG, a digitizer, a control unit, and an ECS (in place around the PT tendon).

**Fig. 7.** Overview of the eddy-current-based tension-force-loss warning algorithm.
chirp signal (varying from 200 to 700 kHz) to the ECS over 10 ms, and the eddy current was measured. The AWG applied a modulated linear and gradually reduced to 20 kN at 20 kN intervals. At each force level, 1 MHz.

A chip capacitor of 200 pF was connected to the driving experiment, a chip capacitor of 200 pF was connected to the driving coil of the ECS to keep its electromagnetic resonant frequency below 45 mm×60 mm. The ring-type ECS described in Section 3.1 was installed on the butt end of the wedge using adhesive. In this experiment, a mono-strand PT tendon was tensioned using a UTM to the initial force level of 180 kN, and then its tension level is gradually decreased to 20 kN at 20 kN intervals.

4. Experimental validation

4.1. Experimental setup

The effectiveness of the proposed EC-TFLW technique was validated experimentally. As shown in Fig. 8, a mono-strand PT tendon was inserted into a steel frame, and tension was applied to the tendon using a custom-designed universal testing machine (UTM). The UTM consists of a 2400×220×220 mm³ steel frame, a hydraulic actuator, and a load cell. The maximum load capacity of the hydraulic actuator was 250 kN, and the rated measurement range of the load cell was from 0 to 300 kN with 0.1 kN load resolution. It was easy for a user to set the desired level of force in the control unit, after which the hydraulic actuator accordingly adjusted the tension force of the tendon to the prescribed level. The tension force measured by the load cell was considered the ground-truth in this experiment.

A 3.3-m long, 15.2-mm diameter, normal-relaxation tendon was used as a test specimen. The tendon had a Young’s modulus of 195 GPa [19]. A wedge and anchor head (KTA-MA-Type produced by Korea Total Anchorage, Inc.) were installed at both ends of the tendon, and its allowable strength was 1860 MPa. When the wedge and the anchor head were fully assembled, the overall size of the assembly was Φ 45 mm×60 mm. The ring-type ECS described in Section 3.1 was installed on the butt end of the wedge using adhesive. In this experiment, a chip capacitor of 200 pF was connected to the driving coil of the ECS to keep its electromagnetic resonant frequency below 1 MHz.

The tension force of the tendon was increased to 180 kN initially, and gradually reduced to 20 kN at 20 kN intervals. At each force level, the eddy current was measured. The AWG applied a modulated linear chirp signal (varying from 200 to 700 kHz) to the ECS over 10 ms, and its amplitude was set to ±6 V. The frequency range was selected to intensify the magnetic field locally (near the wedge surface) with minimum power consumption. The penetration depth calculated using Eq. (2) was approximately between 10 and 30 μm. The eddy current was sampled at 2.5 MHz through the digitizer. To construct the test statistics \( \chi^2_{\text{test}} \) using Eq. (6), measurements of the eddy current was repeated 30 times at each force level. During inspection, the minimum impedance magnitude of the driving coil \( |Z_d| \) was 175 Ω at the minimum driving frequency (200 kHz). From this, the maximum power necessary for an inspection was estimated to be only 410 mW (≈(12 V/2)²/175 Ω).

4.2. Experimental results

At the maximum tension force level of 180 kN, the initial eddy current measurement was taken. Fig. 9 shows a typical eddy current measurement when the driving frequency was swept from 200 to 700 kHz.

The tension force of the tendon was decreased from 180 to 20 kN, at 20 kN intervals, and the eddy current response on the wedge surface was measured using the ECS at each tension force level. Fig. 10 shows the results at different tension force levels (20, 100, and 180 kN). As the tension force decreased from the initial condition, the difference between \( X(t) \) and \( Y(t) \) gradually increased. Consequently, the variance of the difference distribution also increased from \( \sigma_0^2 = 2.05 \times 10^{-5} \) to \( \sigma_{20 \text{ kN}}^2 = 2.44 \times 10^{-5}, \sigma_{100 \text{ kN}}^2 = 2.19 \times 10^{-5}, \) and \( \sigma_{180 \text{ kN}}^2 = 2.07 \times 10^{-5} \)

Next, the statistical hypothesis defined in Eq. (6) was performed for automated warning of the tendon force reduction. In general, about 30% reduction from the initial tendon force level is considered acceptable [20]. Therefore, the threshold value corresponding to 70% confidence interval and 29 DOF was selected, \( \chi^2_{29,0.70} = 32.46 \), in this study. Here, the DOF was set to 29 because the number of measurements at each tested tension force level was 30 (i.e., \( n = 30 \)).

Fig. 11 shows the test statistics obtained at different tension force levels along with the threshold value. To improve the reliability of the...

Fig. 9. Average eddy current measurement, \( X(t) \), at the initial tension force of 180 kN when the driving frequency was swept from 200 to 700 kHz.

Fig. 10. Comparison of the histograms of the differences between \( X(t) \) and \( Y(t) \) at tension force levels of 20, 100, and 180 kN. As the tendon force decreased, its variance monotonomically increased. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).
test, the test statistic was estimated five times at each force level with about a 5-min time gap between two consecutive measurements. When $X^{2}_{stat}$, computed using Eq. (6) became larger than the threshold value, $H_0$ was rejected and a warning signal was sent out. In this experiment, the EC-TFLW technique sent out the first warning signal when the tension force was reduced below 100 kN.

5. Conclusions

In this study, an eddy-current-based tension-force-loss warning (EC-TFLW) technique was proposed to determine automatically excessive tension force loss of a post-tensioning (PT) tendon. The proposed EC-TFLW technique is advantageous because of (1) low cost and low power consumption, (2) simple installation, and (3) potential for embedding in concrete to enable online PT tendon monitoring. The feasibility of the EC-TFLW technique was investigated experimentally by estimating tension force loss of a 3.3-m long, 15.2-mm diameter, mono-strand tendon. Excessive tension force loss (> 80 kN decline from initial tension force) was successfully detected automatically using the proposed hypothesis-testing algorithm, and when warranted, a warning was sent.

For field applications of the proposed EC-TFLW technique, there remain several issues to be investigated in the future. First, for the embedding of ECS in concrete, development of an embeddable sensor module, along with reliable power and data transmission strategies, is necessary. Second, the sensitivity of the proposed EC-TFLW technique to the initial tension force reduction should be improved for earlier warning. Third, the current technique is only applicable to ungrouted PT tendons, and further investigation is warranted for grouted tendons.

Acknowledgement

This study was supported by a grant from the Smart Civil Infrastructure Research Program (13SCIP01), funded by the Ministry of Land, Infrastructure, and Transport (MOLIT) of the government of the Republic of Korea.

References