*Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability – Casas, Frangopol & Turmo (eds)*
*© 2022 copyright the Author(s), ISBN 978-1-032-35623-5*

# Simultaneous displacement and cable force estimation for submerged floating tunnel based on strain and acceleration measurements

Zhanxiong Ma, Jaemook Choi & Hoon Sohn
*Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea*

ABSTRACT: Over the world, there are ongoing efforts to realize the construction of submerged floating tunnels (SFTs). As part of the efforts, it is critical to continuously monitor the integrity of an SFT throughout its life span. The displacement of the SFT itself and the tension forces of the cables connecting the SFT to the ground can provide critical information regarding the condition of the SFT. In this study, a simultaneous displacement and cable force estimation technique is developed for SFTs based on acceleration and strain measurements. Strain measurements are firstly transformed into displacement using a mode superposition algorithm, and then the transformed displacement is fused with acceleration measurement using a finite impulse response (FIR) filter and a recursive least square (RLS) estimation algorithm for improved displacement estimation. Finally, the tension forces of the cables at the connection points between the SFT and the cables are estimated based on the displacement estimated at the connection points. The feasibility of the proposed technique is examined through numerical simulation and a laboratory test on an 8-m long aluminium SFT model.

## 1 INTRODUCTION

Submerged floating tunnels (SFTs) are innovative structures for vehicle crossing through deep water, which offer better crossing capacities and lower construction costs than traditional bridges and tunnels (Østlid 2010). Over the world, there are ongoing efforts to realize the construction of SFTs. As part of the efforts, it is critical to continuously monitor the integrity of an SFT throughout its life span.

Monitoring SFT displacement is essential since displacement provides crucial information regarding the structural integrity and condition of SFT. There are several techniques for direct structural displacement sensing, including a linear variable differential transformer (LVDT), a real-time kinematic global navigation satellite system (RTK-GNSS) (Nakamura 2000), and vision-based system (Feng, Fukuda, Feng, & Mizuta 2015). These days, researchers have also developed indirect structural displacement estimation techniques through the use of accelerometers or strain sensors (Lee, Hong, & Park 2010, Shin, Lee, Kim, & Kim 2012). Since each of these direct and indirect techniques has its own limitations, another trend for structural displacement estimation is to fuse data from different sensors, including the fusion of RTK-GNSS and accelerometer (Kim, Choi, Koo, & Sohn 2016), the fusion of strain gauge and accelerometer (Park, Sim, & Jung 2013, Ma & Sohn 2019, Ma, Chung, Liu, & Sohn 2021), and the fusion of vision camera and accelerometer (Ma, Choi, & Sohn 2021). The majority of these techniques cannot work at underwater environments, and then cannot be used for SFT displacement estimation. One possible solution for SFT displacement estimation is to fuse strain sensors and accelerometers, but its feasibility needs to be verified.

Mooring cables are major load-carriers of SFTs, and it is also essential to monitor tension forces of mooring cables to prevent any catastrophic failures of SFTs. Several cable force estimation techniques using load cells (Cho, Yim, Shin, Jung, Yun, & Wang 2013), strain gauges (Kim, Sung, Kim, & Kim 2011), accelerometers (Kim & Park 2007, Jeong, Kim, Lee, & Sim 2021), electromagnetic (EM) sensors (Yim, Wang, Shin, Yun, Jung, Kim, & Eem 2013), and eddy current sensors (Kim, Lee, & Sohn 2017) have been proposed. However, all these discrete sensors must be physically placed on each cable, and such installation can be time consuming and labor intensive. Several attempts were performed to develop computer-vision (CV) techniques for the noncontact tension force estimation of multiple cables (Feng, Scarangello, Feng, & Ye 2017, Kim, Jeon, Kim, & Park 2013). However, CV techniques can not work at underwater environments.

In this study, a simultaneous displacement and cable force estimation technique is developed for SFTs using strain and acceleration measurements. Strain measurements are firstly transformed into displacement using a mode superposition algorithm, and then the transformed displacement is fused with

DOI: 10.1201/9781003322641-133

acceleration measurement using a finite impulse response (FIR) filter and a recursive least square (RLS) estimation algorithm for high-fidelity displacement estimation. Finally, the tension forces of the mooring cables are estimated based on the displacement estimated at the connection points between the SFT and the cables.

The reminder of this paper is organized as follows. The simultaneous displacement and cable force estimation technique is explained in Section 2. The performance of the proposed technique is firstly examined in Section 3 through a numerical simulation of an 800-m long SFT, and then in Section 4 by conducting an experiment on an 8-m long aluminum SFT model. The concluding remarks are provided in Section 5.

## 2 METHODOLOGY

In this section, a simultaneous displacement and cable force estimation technique is developed for SFTs using strain and acceleration measurements. Multiple strain gauges are installed along the tunnel, and an accelerometer is installed at each point of the tunnel where the displacements need to be estimated. As shown in Figure 1, displacements are firstly estimated using multiple strain and acceleration measurements by combing an FIR filter and a RLS estimation algorithm, and then the tension forces of the mooring cables are estimated based on the displacement estimated at the connection points between the SFT and the cables.

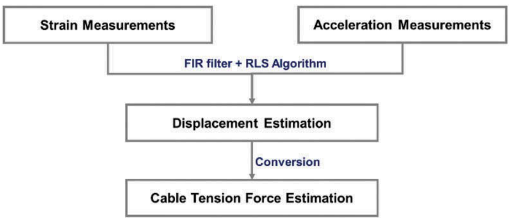


Figure 1. Overview of simultaneous displacement and cable force estimation for submerged floating tunnel.

### 2.1 *Strain–displacement transformation*

Based on Euler–Bernoulli beam theory, the vertical displacement of the beam $u(x,k)$ can be estimated from strain measurements $\varepsilon(x,k)$ using a mode superposition technique (Shin, Lee, Kim, & Kim 2012):

$$u(x,k) = \frac{1}{y_c}\mathbf{\Psi}(x)\mathbf{\Phi}(x)^{-1}\varepsilon(x,k) \quad (1)$$

$$\mathbf{\Phi}(k) = \begin{bmatrix} \frac{d^2\psi_1(x_1)}{dx^2} & \cdots & \frac{d^2\psi_L(x_1)}{dx^2} \\ \cdots & \ddots & \cdots \\ \frac{d^2\psi_1(x_m)}{dx^2} & \cdots & \frac{d^2\psi_l(x_m)}{dx^2} \end{bmatrix}_{m\times L} \quad (2)$$

$$\mathbf{\Psi}(x) = [\psi_1(x)\cdots\psi_L(x)]_{1\times L} \quad (3)$$

$$\varepsilon(x,k) = [\varepsilon(x_1,k)\cdots\varepsilon(x_m,k)]^T_{m\times 1} \quad (4)$$

where $\psi_i$ represents the i$^{th}$ displacement mode shape, $k$ represents the ]itk$^{th}$ time step, $L$ is the number of modes considered and $y_c$ denotes the distance from the strain measurement point to the neutral axis in the vertical direction. Considering the difficulty of obtaining accurate $y_c$ in practice, two strain measurements from different heights of the cross section are used. Then, Equation (1) becomes,

$$u(x,k) = \frac{1}{h}\mathbf{\Psi}(x)\mathbf{\Phi}(k)^{-1}[\varepsilon(x_1,k) - \varepsilon(x_2,k)] \quad (5)$$

where $\varepsilon_1$ and $\varepsilon_1$ denote two strain measurements, and h denotes the distance between the two strain measurement points.

In practice, the true mode shapes of an SFT are unknown. However, its mode shapes can be simplified as the mode shapes of a simply supported beam with a uniform cross-section.The simplified mode shapes have been used to calculate dynamic response of SFTs (Xiang & Yang 2017), and then is adopted in this study. A scale factor $\alpha(x)$ is introduced to account for the differences between the true and simplified mode shapes as follows:

$$u(x,k) = \frac{1}{\alpha(x)h}\mathbf{\Psi}(x)\mathbf{\Phi}(k)^{-1}[\varepsilon(x_1,k) - \varepsilon(x_2,k)] \quad (6)$$

Note that an RLS algorithm is developed in this study to identify the scale factor, and the details are provided in Section 2.2.

### 2.2 *Displacement estimation by combining FIR filter and RLS algorithm*

An FIR filter-based technique has been proposed to estimate displacement from acceleration measurement (Lee, Hong, & Park 2010), and been extended to allow for the fusion of acceleration and strain measurements for improved displacement estimation (Park, Sim, & Jung 2013). In this section, by combining the FIR filter and a RLS algorithm, a displacement estimation technique is proposed using acceleration and strain measurements, and it achieves the simultaneous estimation of the unknown scale factor and the displacement. The flowchart of the proposed technique is shown in Figure 2. First, the strain measurements from the distributed strain gauges are transformed into displacement without the scale factor ($u_s$(x, k)). Next, a low-pass filter, $C_L$, is applied to the unscaled displacement, and a combination of a high-pass filter and double integrator, $C_H$, is applied to the acceleration measurement. More details about these two filters can

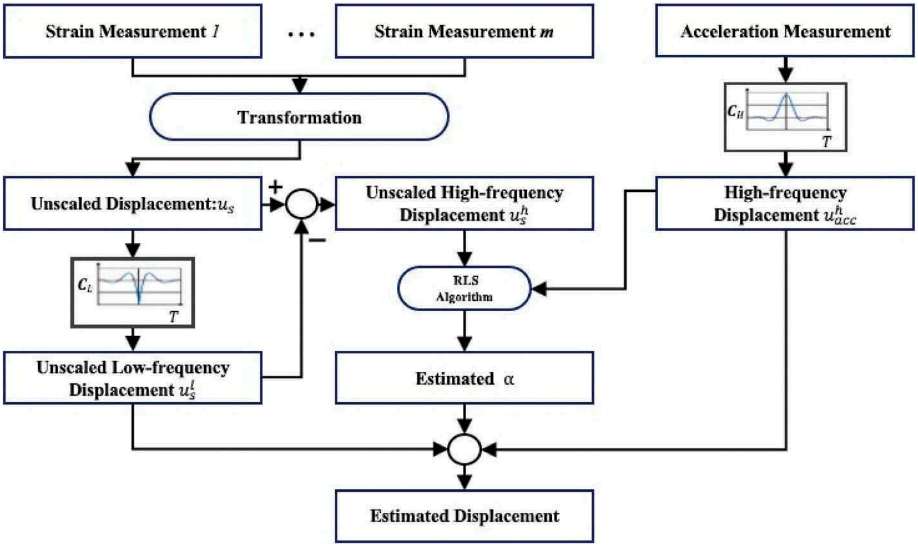


Figure 2. Flowchart of the proposed displacement estimation technique.

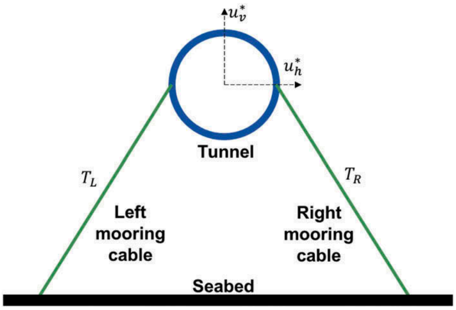


Figure 3. Relationship between cable tension force and tunnel displacement.

be found in (Lee, Hong, & Park 2010). Then, the unscaled low-frequency displacement from the strain measurements, and the high-frequency displacement from the acceleration measurement, are obtained. Additionally, the unscaled high-frequency displacement from the strain measurements $(u_s^h(x,k))$ is obtained by deducing $u_s^l(x,k)$ from $u_s(x,k)$. The scale factor $\alpha(x)$ is estimated by applying the RLS algorithm to $u_s^h(x,k)$ and $u_{acc}^h(x,k)$, and the final displacement is estimated as,

$$u^*(x,k) = \alpha(x)u_s^l(x,k) + u_{acc}^h(x,k) \tag{7}$$

### 2.3 *Tension force estimation*

Though various sensors have been developed for cable tension force estimation, they must be physically placed on each cable, and such installation can be time consuming and labor intensive. For mooring cables of a SFT, tension forces can be estimated using displacements at the connection points between the SFT and cables. As shown in Figure 3, tunnel displacements ($u_{\mathrm{v}}^*$ and $u_{\mathrm{h}}^*$) will cause mooring cable length variance, and the length variance can be used to estimate cable tension forces ($T_L$ and $T_R$).

## 3 NUMERICAL VALIDATION

### 3.1 *Model description*

An 800-m long submerged floating tunnel model with a uniform cylinder cross-section is simulated using ABAQUS, as shown in Figure 4. The tunnel is modeled with beam element B31, and the mooring cables were modeled with truss element T3D2. The SFT consists of 30 mooring cables, labeled as C1-C30 from the left to the right, and for each mooring cable, one end is pin-connected with the tunnel and the other end uses a hinge boundary condition. A simply-supported boundary condition is applied to two ends of the tunnel. The strain gauges are placed at locations S1-S7, while an accelerometer is placed at location 16. Note that four strain gauges are installed at each of

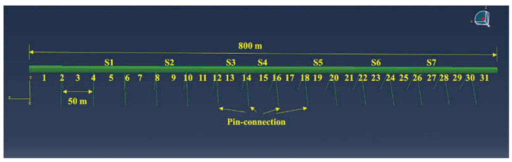


Figure 4. Overview of an 800-m long numerical SFT model.

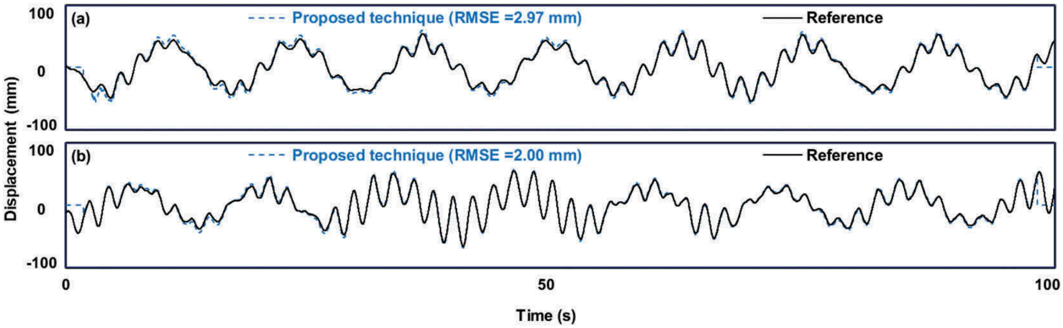


Figure 5. Displacements estimated at location 16 of the numerical SFT model in (a) horizontal and (b) vertical directions.

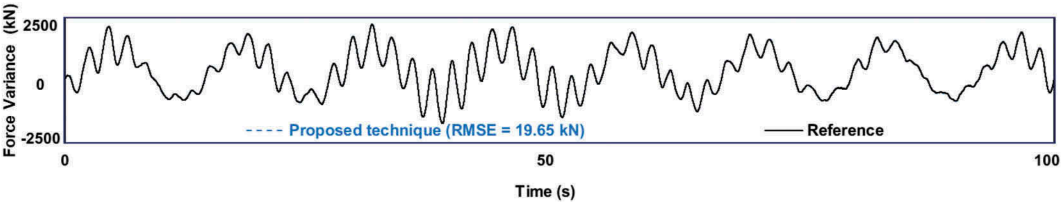


Figure 6. Tension force estimated at cable C15 of the numerical SFT model.

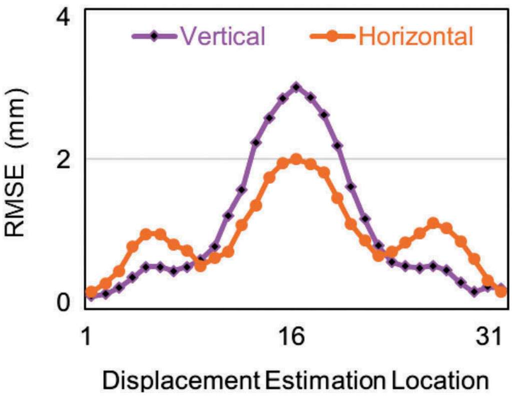


Figure 7. Displacement estimation accuracy at different locations of the numerical SFT model.

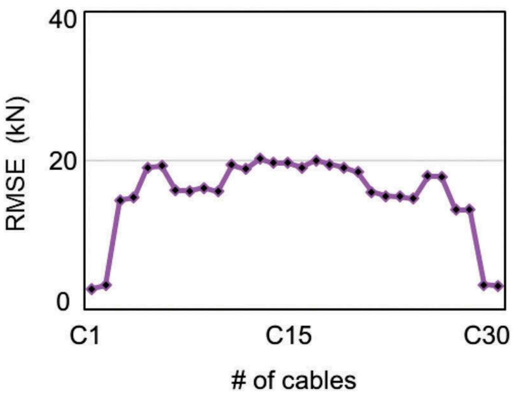


Figure 8. Tension force estimation accuracy at different cables of the numerical SFT model.

locations S1-S7 for bi-directional displacement estimation. The acceleration, strain and displacement responses of the tunnel and tension forces of mooring cables are simulated at 100 Hz when the model is subjected to wave and current loadings, and a uniform distributed loading with amplitude randomly changing. Gaussian noises are added to the acceleration and strain responses to simulate measurement noises. As accelerometers usually have higher signal-to-noise ratios (SNRs) than those of strain gauges, the SNR is set to 10 for strain responses and 20 for acceleration responses.

### 3.2 *Estimation results*

Firstly, the displacement is estimated at location 16 using acceleration measurement at the same location and the strain measurements at locations S1-S7. As shown in Figure 5, good agreements are observed between the estimated and reference displacements in both vertical and horizontal directions, with root mean square errors (RMSEs) smaller than 3 mm. The estimated tension force at the cable C15 using the estimated displacements at location 16 is shown in Figure 6, and it is estimated accurately as well with around 20 kN RMSE.

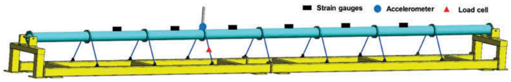


Figure 9. Overview of the 8-m long SFT model and sensor installation locations.

Next, the accelerometer is moved from location 1 to location 31 to estimate displacements at all these locations, and tension forces in all 30 mooring cables. The RMSEs of the estimated displacements are summarized in Figure 7, and they are below 3 and 2 mm in vertical and horizontal direction, respectively. Finally, the estimated displacements at the connection points between the SFT and the cables are used to estimate tension forces of all mooring cables. The RMSEs of the estimated tension forces are summarized in Figure 8, and they are below 20 KN.

## 4 EXPERIMENTAL VALIDATION

### 4.1 *Model description*

The proposed technique is then experimentally validated on an 8-m long submerged floating tunnel. The tunnel is made of an aluminum whose density is close to that of concrete. It consists of eight 1-m long segments, which are welded together. The tunnel has cylinder cross-section with an outside diameter of 14 cm and a thickness of 0.5 mm. Both ends of the tunnel are hinge-connected to steel bracket platforms to achieve simply-supported boundary condition. Stainless steel wires with a diameter of 0.5 mm are used as mooring cables, and a total of 14 mooring cables are used. For each mooring cable, one end is connected to the tunnel by metal ring buckles and the other end is connected to a steel bracket platform fixed to the bottom of the water channel using multiple anchor bolts. An accelerometer is installed the connection point between the third and fourth segments for displacement estimation at the same location, while strain gauges are installed at six locations as shown in Figure 9. A load cell is installed at the cable where tension force needs to be estimated. A 20-cm long steel bar is mounted at displacement estimation location as a target for a camera installed at a fixed location to provide reference displacement. Note that during the experiment, the SFT tunnel is always submerged in water and the top of the steel bar is always above the water surface.

### 4.2 *Estimation results*

The estimated displacements using acceleration measurement at same location and the strain measurements at six locations are shown in Figure 10. The proposed technique estimates displacement accurately in both horizontal and vertical directions with RMSEs below 0.1 mm. The estimated cable tension force using the estimated displacements is shown in Figure 11, and a good agreement is observed between the estimated tension force and the reference from the load cell.

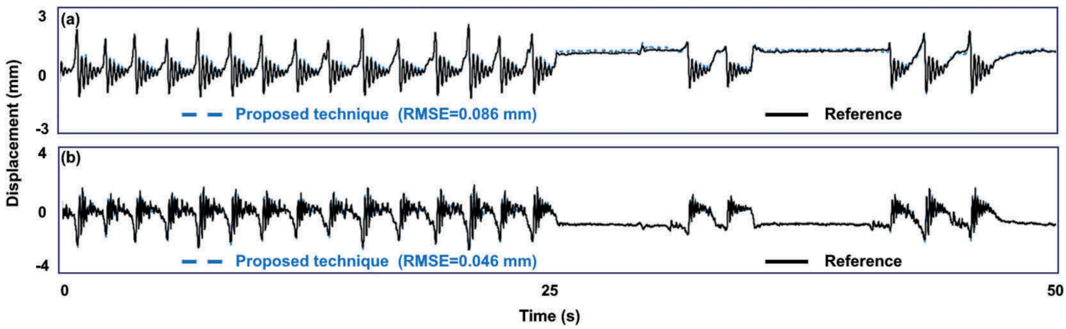


Figure 10. Displacements estimated on the 8-m long SFT model in (a) horizontal and (b) vertical directions.

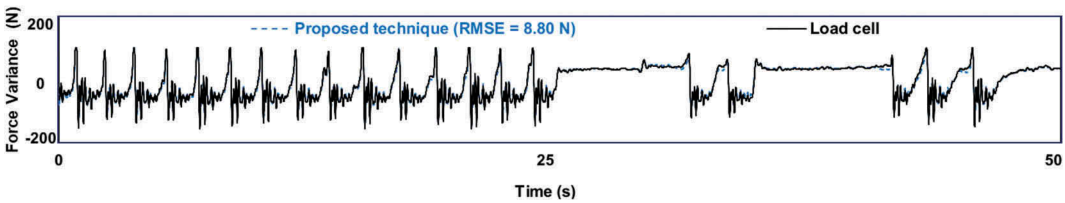


Figure 11. Tension force estimated on the 8-m long SFT model.

## 5 CONCLUSIONS

In this paper, a simultaneous displacement and cable force estimation technique is developed for SFTs based on acceleration and strain measurements. Strain measurements are firstly transformed into displacement using a mode superposition algorithm, and then the transformed displacement is fused with acceleration measurement using an FIR filter and a RLS estimation algorithm for improved displacement estimation. Finally, the tension forces of the cables are estimated based on the displacement estimated at the connection points between the SFT and the cables. The feasibility of the proposed technique was firstly examined using an 800-m long numerical SFT model. Bi-directional displacements are estimated at 31 locations, and tension forces are estimated at 30 mooring cables. The RMSEs are smaller than 3 mm and 20 kN for displacement and tension force estimation, respectively. The performance of the proposed technique is further validated on an 8-m long aluminum SFT model. Both displacements and tension force are accurately estimated with RMSEs smaller than 0.1 mm and 9 N, respectively.

## ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Koran Government (MSIT) (No. 2017R1A5A1014883).

## REFERENCES

Cho, S., J. Yim, S. W. Shin, H.-J. Jung, C.-B. Yun, & M. L. Wang (2013). Comparative field study of cable tension measurement for a cable-stayed bridge. *Journal of Bridge Engineering 18*(8), 748–757.

Feng, D., T. Scarangello, M. Q. Feng, & Q. Ye (2017). Cable tension force estimate using novel noncontact vision-based sensor. *Measurement 99*, 44–52.

Feng, M. Q., Y. Fukuda, D. Feng, & M. Mizuta (2015). Nontarget vision sensor for remote measurement of bridge dynamic response. *Journal of Bridge Engineering 20*(12), 04015023.

Jeong, S., H. Kim, J. Lee, & S.-H. Sim (2021). Automated wireless monitoring system for cable tension forces using deep learning. *Structural Health Monitoring 20* (4), 1805–1821.

Kim, B. H. & T. Park (2007). Estimation of cable tension force using the frequency-based system identification method. *Journal of sound and Vibration 304*(3-5), 660–676.

Kim, J.-M., J. Lee, & H. Sohn (2017). Automatic measurement and warning of tension force reduction in a pt tendon using eddy current sensing. *Ndt & E International 87*, 93–99.

Kim, K., J. Choi, G. Koo, & H. Sohn (2016). Dynamic displacement estimation by fusing biased high-sampling rate acceleration and low-sampling rate displacement measurements using two-stage kalman estimator. *Smart Struct. Syst 17*(4), 647–667.

Kim, S.-W., B.-G. Jeon, N.-S. Kim, & J.-C. Park (2013). Vision-based monitoring system for evaluating cable tensile forces on a cable-stayed bridge. *Structural Health Monitoring 12*(5-6), 440–456.

Kim, Y.-S., H.-J. Sung, H.-W. Kim, & J.-M. Kim (2011). Monitoring of tension force and load transfer of ground anchor by using optical fbg sensors embedded tendon. *Smart Structures and Systems 7*(4), 303–317.

Lee, H. S., Y. H. Hong, & H. W. Park (2010). Design of an fir filter for the displacement reconstruction using measured acceleration in low-frequency dominant structures. *International Journal for Numerical Methods in Engineering 82*(4), 403–434.

Ma, Z., J. Choi, & H. Sohn (2021). Real-time structural displacement estimation by fusing asynchronous acceleration and computer vision measurements. *Computer-Aided Civil and Infrastructure Engineering*.

Ma,ffdre Z., J. Chung, P. Liu, & H. Sohn (2021). Bridge displacement estimation by fusing accelerometer and strain gauge measurements. *Structural Control and Health Monitoring 28*(6), e2733.

Ma, Z. & H. Sohn (2019). Structural displacement estimation by fir filter based fusion of strain and acceleration measurements. In *The 29th International Ocean and Polar Engineering Conference*. OnePetro.

Nakamura, S.-i. (2000). Gps measurement of wind-induced suspension bridge girder displacements. *Journal of structural Engineering 126*(12), 1413–1419.

Østlid, H. (2010). When is sft competitive? *Procedia Engineering 4*, 3–11.

Park, J.-W., S.-H. Sim, & H.-J. Jung (2013). Displacement estimation using multimetric data fusion. *IEEE/ASME Transactions On Mechatronics 18*(6), 1675–1682.

Shin, S., S.-U. Lee, Y. Kim, & N.-S. Kim (2012). Estimation of bridge displacement responses using fbg sensors and theoretical mode shapes. *Structural engineering and mechanics: An international journal 42*(2), 229–245.

Xiang, Y. & Y. Yang (2017). Spatial dynamic response of submerged floating tunnel under impact load. *Marine Structures 53*, 20–31.

Yim, J., M. L. Wang, S. W. Shin, C.-B. Yun, H.-J. Jung, J.-T. Kim, & S.-H. Eem (2013). Field application of elasto-magnetic stress sensors for monitoring of cable tension force in cable-stayed bridges. *Smart structures and systems 12*(3), 465–482.