가속도 및 변형률 측정을 이용한 수중터널의 변위 및 케이블장력 추정

Displacement and Cable Tension Estimation for Submerged Floating Tunnel Using Acceleration and Strain Measurements

Zhanxiong Ma*, 최재묵*, 손훈*†

Zhanxiong Ma*, Jaemook Choi*, and Hoon Sohn*†

*한국과학기술원 건설및환경공학과

*Korea Advanced Institute of Science and Technology, Department of Civil and Environmental Engineering

†Corresponding author: hoonsohn@kaist.ac.kr

Abstract: A submerged floating tunnel (SFT) can be an attractive alternative to conventional bridges or immersed tunnels. Efforts to build SFTs are underway around the world, and the monitoring of tunnel displacement and mooring cable tension force would be critical to assess the structural integrity of the SFT. In this study, tunnel displacement and mooring cable tension force are simultaneously estimated by fusing acceleration and strain measurements. First, displacement is estimated from multi-point strain measurements using simplified mode shapes and mode scaling factors without requiring true mode shapes of the SFT. Here the mode scaling factors are automatically estimated using initial strain and acceleration measurements. The estimated displacement from the strain measurements is then fused with single-point acceleration measurement using a finite impulse response (FIR) filter to obtain a final displacement with higher accuracy. In addition, the tension force of a mooring cable is estimated from the displacement at the connection between the tunnel and the mooring cable. The feasibility of the proposed technique was examined through a series of numerical simulations and laboratory tests on an 8-m-long aluminum SFT mock-up structure.

Keyword: Submerged floating tunnel, displacement, cable tension, strain gauge, accelerometer, FIR filter.

1. Introduction

Submerged floating tunnel (SFT) is an attractive alternative to conventional bridges or immersed tunnels because its construction is not limited by the span length or depth of the ocean floor [1]. The development of monitoring systems to continuously evaluate the integrity of these SFTs is necessary. Monitoring SFT displacement is essential since displacement provides crucial information regarding the structural integrity and condition of SFT. Though there are several techniques for direct measurement using LVDT, GNSS and vision camera, and indirect estimation techniques using accelerometer and strain sensorss However, most of them cannot work at underwater environments, and the fusion of strain gauges and accelerometer [1] seems to be promising for SFT displacement monitoring. Monitoring of the mooring cable tension is also essential because mooring cables are major load-carrying members. Several cable tension estimation techniques have been proposed, utilizing load cells, strain gauges, etc. However, all of these discrete sensors must be physically placed on each cable, and such an installation can be time-consuming and labor-intensive. Although computer-vision techniques have been developed for noncontact tension estimation, they cannot work in underwater environments. This paper describes a displacement and cable tension estimation technique for SFTs using strain and acceleration measurements, and details of the proposed technique are explained in Section 2.

2. Methodology

Fig. 1 shows the flowchart of the proposed technique. Strain measurements are firstly transformed into displacement using a mode superposition algorithm, and then the transformed strain-based displacement is fused with acceleration measurement using a FIR filter [2] for high-fidelity displacement estimation. Finally, the tensions of the mooring cables are estimated based on the displacement estimated at the connection points between the SFT and the cables. Note that the strain-displacement requires mode-scaling factors and their values are automatically estimated using initial strain and acceleration measurements.

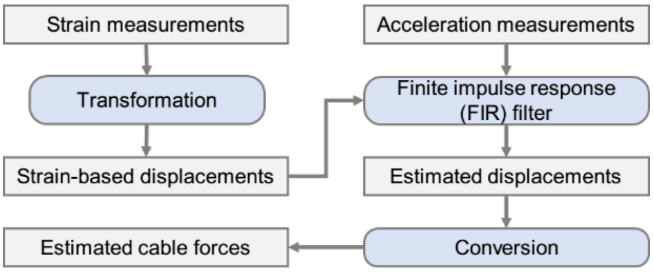

Fig. 1 Flowchart of the proposed technique for SFT

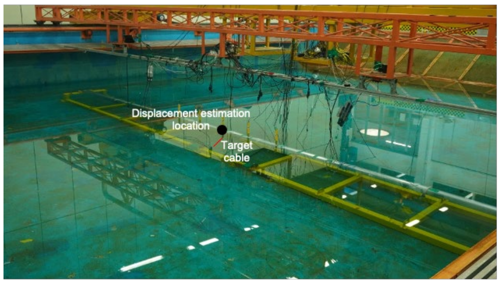

Fig. 2 SFT mock up structure installed at a 3D ocean basin

3 Experimental validation

The performance of the proposed technique was validated on an 8-m-long aluminum SFT mock-up structure installed at a 3D ocean basin (shown in Fig. 2). The displacement estimation location and the target cable are shown in Fig. 2, and the estimation results when the structure was manually pushed and released in a vertical direction are shown in Figs. 3 and 4. They are in good agreement with the references measured by a vision camera and a load cell, respectively, and normalized root mean square errors (NRMSE) are 2.45% and 3%, respectively.

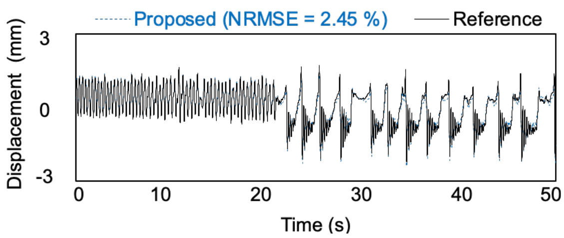

Fig. 3 Displacement estimation result

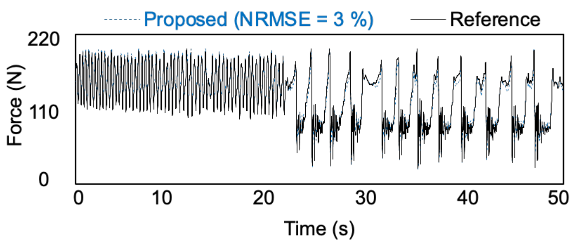

Fig. 4 Mooring cable tension estimation result

4. Conclusion

In this study, a displacement and mooring cable tension estimation technique was proposed for SFTs through the fusion of strain and acceleration measurements. The performance of the proposed technique was experimentally validated on 8-m-long aluminum SFT mock-up structure, and the proposed technique accurately estimated displacement and mooring cable tension with 2.45% and 3% NRMSEs, respectively. Future works are warranted to further validate the proposed technique under more realistic loadings such as wave and vehicle loadings.

Acknowledgement

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

Reference

1. Ma Z, Chung J, Liu P, Sohn H. Bridge displacement estimation by fusing accelerometer and strain gauge measurements. Structural Control & Health Monitoring 2021; 28(6): e2733.
2. Lee HS, Hong YH, Park HW. Design of an FIR filter for the displacement reconstruction using measured acceleration in low-frequency dominant structures. International Journal for Numerical Methods in Engineering 2010; 82(4): 403–434.